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UNIVERSITY
OF TECHNOLOGY

PUBLICATION 107
STRUCTURAL ENGINEERING

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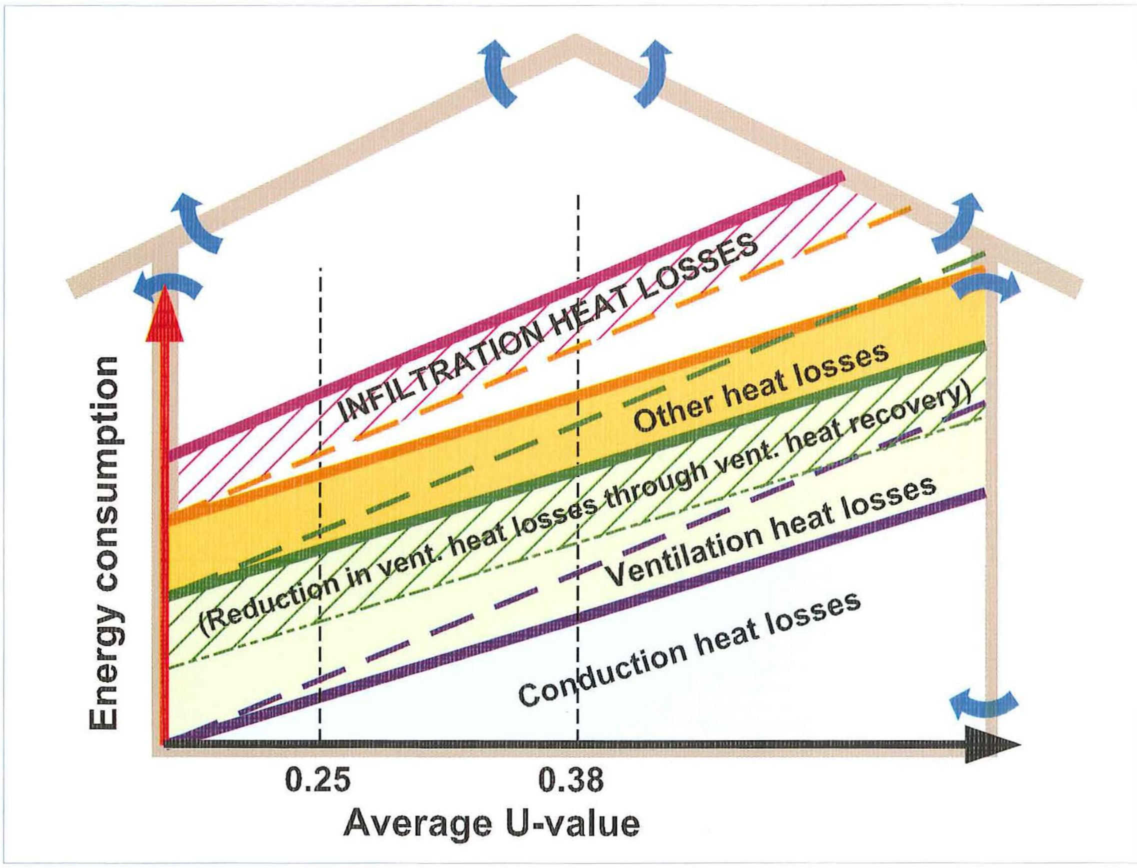

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UDK 697.12
ISBN 952-15-0554-0
ISSN 1237-1483

PREFACE AND ACKNOWLEDGEMENTS

This study is based on research work that was carried out at the Tampere University of Technology (TUT), Department of Civil Engineering, Institute of Structural Engineering during the years 1999-2000.

The study deals with the assessment of the impact of the air tightness of the building envelope on the efficiency of balanced mechanical supply and extract ventilation systems with heat recovery (MVHR) in residential buildings. The goal was to establish the technical viability of implementing MVHR systems in residential buildings by carefully observing important factors consisting of the degree of envelope air tightness, air leakage, heat recovery performance, and climatic weather. These were considered to be the main factors, which have a significant effect on the heating energy consumption in buildings.

Measures to optimise the energy used for heating/warming buildings were the central focus of the study. Therefore, the work extended further into examining the implication of envelope air tightness to the overall heating energy consumption in residential buildings.

The work was supervised by Professor Ralf Lindberg, head of both TUT Civil Engineering Department and the Institute of Structural Engineering. Colleagues, Minna Teikari and Hannu Keränen offered a great assistance in installation of the ventilation systems into the test buildings and data collection.

The financial support from the Finnish Technology Development Centre (TEKES), SPU-Systems Oy, H+H Siporex Oy, and LVI-PARMAIR Oy is gratefully acknowledged. The project was organised and managed by a steering group, which consisted of the following persons:

Ilkka Pohjoismäki	H+H Siporex
Jussi Kurikka	H+H Siporex
Lasse Pöyhönen	TEKES
Markku Kari	LVI-PARMAIR OY
Ralf Lindberg	TTKK
Tapani Tuominen	SPU-Systems OY

Sincere thanks are due to the steering group members and all those who contributed in one way or another to the success of this research work.

Tampere,
February 2001

Augustino Binamu　　　　Ralf Lindberg

ABSTRACT

Ventilation heat recovery is the process by which heat energy is recovered from the exhaust air for re-use to preheat the incoming cold supply air. Among other factors, air infiltration can greatly impair the total performance of a ventilation heat recovery system and in some cases, it can cause the recovery process to expend more energy than that recovered. Moisture problems and severe contamination of the indoor air can also result from air leakage through the building envelope.

This study investigated the impact of envelope air tightness on energy performance of ventilation systems with heat recovery. The research involved various measurements including indoor and outdoor temperatures, the supply and extract air temperatures before and after heat recovery, wind speed and direction, solar radiation, building air tightness, infiltration/exfiltration, and heat energy used to heat the buildings. The tests were carried out in three experimental buildings constructed of different building materials and having different degree of air tightness. The air tightness of these buildings was determined by pressurisation method. The uncontrolled air change rate (air leakage) was measured by using tracer gas method. Balanced mechanical ventilation systems with air-to-air heat recovery were used to ventilate the buildings.

Two equations were derived in the study. One for theoretical prediction of uncontrolled air change based on the pressurisation test data. The other one is for estimating the annual heating energy that is needed for heating infiltration air caused by various wind speeds. Comparison of the results obtained through the two derived equations correlated very well with those obtained by using other equations that were found in the existing literature.

The results revealed that a significant quantity of heating energy in buildings is lost due to uncontrolled air changes. For example, it was found that the annual quantity of heating energy loss due to infiltration/exfiltration in a building with 11.1 h^{-1} (ach) degree of air tightness, is approx. 28.076 kWh/m^3 annually. On the other hand, the annual quantity of heating energy loss due to infiltration/exfiltration in buildings that had 0.93 and 1.2 h^{-1} air tightness was 2.324 kWh/m^3 and 3 kWh/m^3 respectively.

The results also showed that the energy savings through implementation of mechanical ventilation systems with heat recovery systems (MVHR) is significant enough to merit the adaptation of these systems in all Finnish residential buildings. In this case, it should however be emphasised that careful attention must be paid to the degree of envelope air tightness. In addition, it was found that the absolute quantity of energy savings through ventilation heat recovery increased as the outdoor temperature decreased. The heat recovery (HR) efficiencies of the ventilation systems tested were found to vary within the range between 42.5% and 70% depending on the outdoor temperature.

The air tightness of the building envelope was found to have a great impact on the overall performance of a ventilation system including the global energy consumption in a building. An increase in air infiltration was found to be directly proportional to the increase in heating energy demand of a building. It was concluded that for potential energy savings through ventilation heat recovery, the degree of envelope air tightness of buildings that are ventilated by MVHR should strictly not exceed 1.5 h^{-1} (ach) at 50 Pa pressure difference. Also, it was confirmed that the colder the outdoor climate the greater the necessity for implementing mechanical ventilation systems with heat recovery to ventilate buildings. The research findings also suggest that there is a need for improvements in the quality of building envelopes and, in particular, the degree of air tightness and insulation levels.

Key words: Air change heat loss, air flow, air leakage, air tightness, annual energy saving, building envelope, energy consumption, heating energy, heating degree-days, heat recovery, infiltration/exfiltration, indoor climate, mechanical ventilation systems, pressure difference, temperature difference, ventilation heat loss, wind speeds

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INTRODUCTION

1.1 General

In recent years, the use of mechanical ventilation systems with heat recovery (MVHR) in residential buildings has increased, especially in countries located in very cold climate. This has mainly been triggered by the growing concern over the heating energy loss due to ventilation and the alarming environmental consequences of energy use. The goal has been directed towards providing sufficient ventilation that is necessary for ensuring health and comfort of building occupants including prevention of mould growth and condensation problems in buildings without energy penalty.

Although the energy efficiency of mechanical ventilation systems is increasingly been improved (i.e. through heat recovery), often their real performances do neither meet the design specifications nor fulfil the users expectations. In part, this is caused by the lack of sufficient knowledge concerning all factors that affect ventilation performance and energy losses. In particular, the impact of the air tightness of building envelope on efficiency of ventilation systems with heat recovery. There is a lack of systems integration with buildings at the design stage so as to form what is known as "integral system". No experimental data, which shows the relationship between various degrees of envelope air tightness and the actual quantity of energy that, can be saved. As a result standards and regulations have failed to set effective boundary conditions for building envelope air tightness where MVHR should be used. In many cases, the outcome has been that more energy is expended than that recovered.

Estimation of the quantity of heating energy loss due to air infiltration has to date been difficult to perform due to lack of simple methods for predicting the quantity of uncontrolled air change. Usually, tracer gas methods or computer programs are used for this task. The drawbacks for these methods are that they either require specialised personnel to execute or too much input data that is not always available. Hence the need for a simple method that can be used to estimate the quantity of air leakage due to the prevailing weather conditions is inevitable.

Improvements in ventilation systems' energy efficiency coupled with increased envelope air tightness constitute a great potential for reducing the energy use due to air change. If buildings envelopes are not sufficiently airtight they will have a negative impact not only on energy use but also on buildings' structural components and the overall performance of mechanical ventilation systems. Moreover, the health of building occupants is subjected to a great risk.

1.2 Research background

Energy-efficient designs and construction stipulates tighter building envelopes and use of mechanical ventilation systems with heat recovery (MVHR) in residential buildings as a measure to conserve energy used for heating. However, despite the advantages of MVHR, these systems have generally not been widely used in residential and other envelope-dominated structures. Less than 10% of the Finnish housing stock is equipped with MVHR [Kohonen 1990]. Problems arise because formula type approach is used in the building design rather than taking into accounts regional differences, operational variations, and the interrelationships between mechanical ventilation systems and the building envelope. The role of air tightness measures and their application in energy savings has not explicitly been understood and tightness measures are often applied without due consideration to ventilation needs or ventilation approach.

In some countries with very cold climates the law demand construction of buildings with high degree of air tightness with the provision of MVHR to ensure sufficient ventilation and energy savings [Swedish Building Code, 1988 and National Building Code of Canada, 1985]. The Belgian Institute for Standardisation also gives some building air tightness guidelines for specific cases but without particular requirement [Bossaer *et al*, 1998]. For instance, for houses operating under balanced mechanical ventilation, the air change rate at 50 Pa pressure difference, n_{50}, should be less than 3 air change per hour (ach), while for buildings operating under balanced mechanical ventilation system with heat recovery the n_{50} should be less than 1 ach. The Finnish Building Code Part D2** [1985] recommends the use of 0.1 h^{-1} and 0.2 h^{-1} for infiltration air changes in the calculations for heating energy for empty buildings and buildings in use respectively.

As the insulation qualities of buildings have improved the proportion of energy lost by air exfiltration has increased, reaching 40-50% of the total energy requirement for the building [Awbi 1991, Virtanen 1993]. Air infiltration can greatly impair the total energy performance of the MVRH and in some cases, the recovery process could expend more energy than the actually recovered [Liddament 1996]. Moisture problems and severe contamination of the indoor air can also result from air leakage through the building envelope. Infiltration can undermine the thermal insulation, can lead to interstitial damp and rot and even the creation of destructive ice boils within the façade [Brundrett 1999]. The optimum performance of MVRH as well as energy control and comfort conditions is dependent on the air tightness of the building envelope. Excessively leaky buildings will interfere with the performance of modern mechanical ventilation systems and will greatly reduce the net efficiency of heat recovery devices [Limb 1994, Liddament 1996, and Virtanen 1993]. Air infiltration due to poor air tightness of the building envelope adds further to lack of control and energy waste and can contribute to noises, discomfort and concealed condensation problems [Malcolm 1998, Orr et al 1980, Riffat *et al* 1990].

Heating energy consumption in a building is a function of all energy losses of the building through different ways. In an airtight building, the heating energy losses are composed of conduction losses (approx. 40%), ventilation losses (approx. 40%), and other losses (i.e. hot wastewater – 20%). In a leaky building, there is an extra energy loss through the infiltration/exfiltration air as discussed above, also as illustrated in Figure 1.1 below.

Conduction heat losses are largely dependent on the coefficient of thermal transmittance (U-value) of the building. Whereas the U-value depends on the building design and the materials used for its construction.

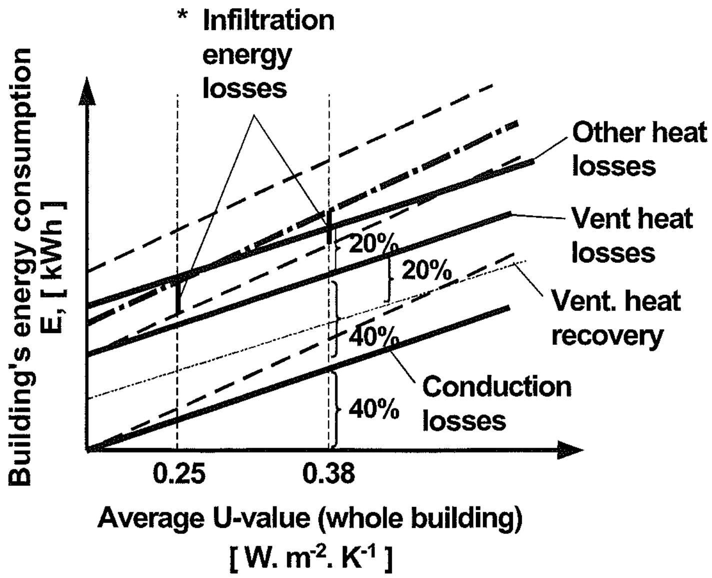


Figure 1.1: Heating energy losses in a building

The lower the average U-value of the building the lower the conduction heat losses while the higher the U-value the higher the conduction heat losses. In insufficiently tight buildings, even with low U-values, conduction heat losses becomes higher than in sufficiently tight buildings as the indoor temperature is kept higher (i.e. up to 24 °C) in order to compensate for the cold infiltrating air draughts. For example, the general air temperature that can satisfactorily be compensated by general air movement inside a building is about 28 °C [McIntyre, 1980].

Ventilation heat losses are dependent on the building air tightness, climate, ventilation strategy used, and the design ventilation air change rate. However, part of the ventilation heat losses can be recovered if heat recovery systems are used. For airtight buildings where ventilation systems with heat recovery have been implemented, up to 70 % of ventilation heat losses can be recovered [McIntyre 1986, Liddament 1986, Irving 1994]. In leaky buildings, the additional infiltration heat losses cannot be recovered even if ventilation systems with heat recovery are implemented. This is due to the fact that heat recovery is possible only from the air that passes through the heat recovery system. In fact, ventilation systems with heat recovery shouldn't be used in leaky buildings as it could result in more energy been used than that recovered (energy penalty).

This research focused on devising a method for determining the quantity of uncontrolled air change (infiltration/exfiltration) in buildings. Further, it evaluates air leakage impact on energy performance of MVHR both theoretically and experimentally. The key factors considered in the heat recovery performance analysis of the systems were the air tightness of the building and climatic weather. Though often stated by manufacturer, that 60-70% of the heat used for space warming can be recovered, on-site experimental test has not been conducted for verification nor are conditions for optimum performance in relation to the building design stated. Liddament [1991] highlighted the fact that high ventilation rate to remove and dilute indoor air pollutants can be expensive to maintain. The cost of conditioning these high ventilation requirements should be borne in mind when considering the role of ventilation in controlling indoor air quality problems in buildings. Clearly, good design will minimise the heating energy losses, yet without explicit guidance there is little that can be accomplished to improve design methods.

1.3 Heat recovery performance of ventilation systems

Ventilation heat recovery is the process by which heat energy is transferred from the exhaust air to the incoming cold supply air. This process takes place in the so-called heat exchanger device usually installed into balanced and/or exhaust mechanical ventilation systems with the aim of preheating the supply air, reducing the quantity of energy required for heating. The technology was formerly widely used in industrial and large public buildings. In recent years however, its application in residential buildings has enormously increased as its potential for energy saving has become more evident. Several methods exist, however, the most popular are air-to-air HR, in which heat recovered from the exhaust air is used to preheat incoming supply air, and heat pumps, in which heat from the exhaust air is used to preheat domestic hot water or space heating.

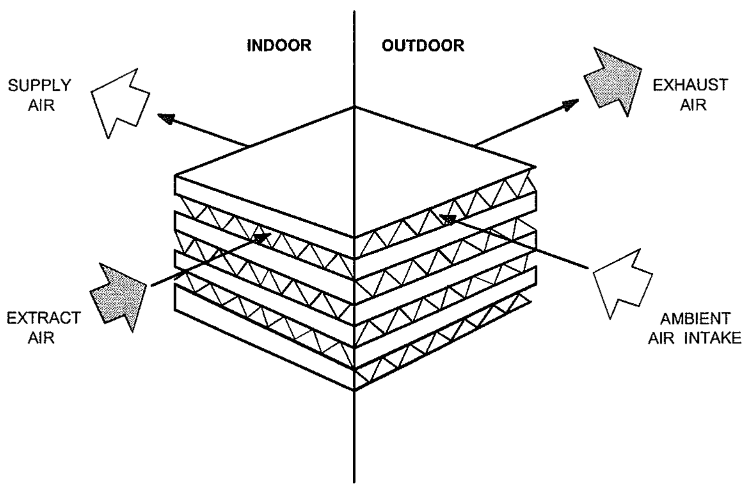


Figure 1.2: Typical residential plate heat exchanger.

Different approaches to air-to-air heat recovery are in use and a reviewed in detail by [Irving 1994, McIntyre 1986]. The most common form of air-to-air heat exchanger used in residential ventilation heat recovery is the plate heat exchanger shown in Figure 1.2. Plate heat exchangers consist of a series of thin metal plates, separated by interleaved small gaps through which the supply and exhaust air flows. The two air flows pass through adjacent gaps, separated by only one plate, through which heat transfer takes place by conduction. The efficiency of a plate heat exchanger is primarily associated with the flow configuration of exhaust and supply air, spacing between plates, the surface area and the type of surface. For example surface roughness can promote turbulence and enhance heat transfer coefficients [Liddament 1996].

Heat can only be recovered from the air that passes through the heat recovery device of a ventilation system. Heat contained within the exfiltration air through other leakage paths is not recovered and, if great in magnitude, will have a considerable impact on the energy performance of a heat recovery system. Hence the importance of air tightness in buildings where ventilation systems with heat recovery are to be used must be emphasised. Less tight buildings could lead to a negative impact on energy performance of heat recovery systems as illustrated in Figure 1.3.

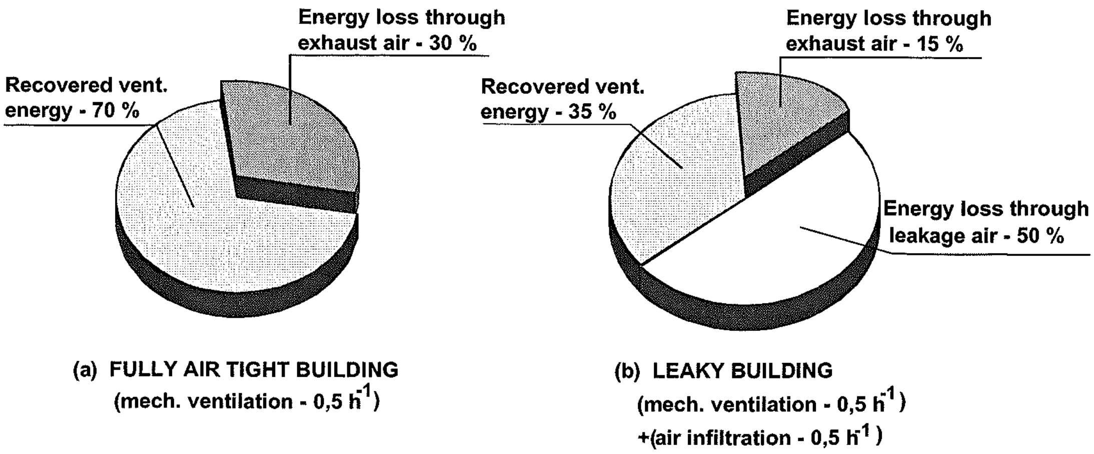


Figure 1.3: Impact of infiltration/exfiltration air on air-to-air heat recovery performance of a ventilation system.

Consider two buildings A and B both having a design mechanical ventilation rate of 0.5 h^{-1}, Figure 1.3. Further, assume that building A is fully air tight and building B is leaky in which air infiltration itself is 0.5 h^{-1}. As demonstrated in Figure 1.3 (a), if the entire design airflow is passing through the heat recovery system, there will be a 70% ventilation energy recovery. If only half of the total air flow (design airflow + infiltration air) is passing through the heat recovery system, Figure 1.3 (b), the resulting ventilation energy recovery will be only 35%. This demonstrates how the energy performance of a ventilation heat recovery system can dramatically be reduced in buildings, which are not sufficiently airtight. In very leaky buildings, more energy could be spent by the HR system than that recovered.

Though the performance of a heat recovery system may be considered largely independent of the outside weather conditions, it should be realised that the absolute amount of heat recovered reduces as the outside temperature increases. However, the energy used by the system (i.e. fan power, ancillary energy etc.) remains constant no matter what is the outside condition. This implies that as the outside temperature rises, the net energy recovery actually decreases and can indeed become negative. The colder the outdoor climate the higher the recovered energy.

Heat recovery performance of a ventilation system is often expressed in terms of percentage efficiencies of heat recovery or coefficients of performance if a heat pump is incorporated. The full benefits of ventilation systems with heat recovery can only be achieved if the systems are installed in sufficiently airtight buildings and properly maintained. In order to make a correct decision regarding the air-to-air heat/energy recovery; hourly weather data should be used with building simulation packages to choose the exchanger that will give the greatest energy savings while having the least life-circle cost. Wheel heat exchangers are favourable when the outdoor humidity is high because it can transfer both sensible and latent energy; whereas, a plate heat exchanger is favourable when the outdoor humidity is low (i.e. outdoor humidity ratio less than indoor humidity ratio) and the latent heat transfer is small [Irwin *et al* 1998].

1.4 Objectives of the study

The potential for cost-effectiveness of ventilation systems with heat recovery depends on the scope of energy savings. In turn, this is a function of the air tightness of the building, the overall ventilation rate, air leakage, and the severity of the climate. The technical viability of implementing mechanical supply and extract ventilation systems with HR in residential buildings can be established by carefully observing important factors such as the heat recovery performance, the impact of air tightness, and the climatic weather. Thus the objectives of this study were to:

- Device a method for determining the quantity of uncontrolled air changes in building and hence calculate the annual quantity of heating energy loss due to air leakage.
- Investigate the influence of the degree of envelope air tightness on heat recovery performance of ventilation systems and its impact on the total heating energy consumption of buildings.
- Determine the yearly heating energy loss due to ventilation (mechanical and infiltration) and evaluate the influence of the severity of the climate on heat recovery efficiency of MVHR systems.

2. THEORETICAL BACKGROUND

2.1 Infiltration and air exchange in buildings

Infiltration and airflow in buildings is governed by the distribution and air flow characteristics of all openings within the building envelope and the pressure difference acting across each opening. These openings include cracks, joints, holes and gaps; intentionally provided air vents; and any open windows and doors. The pressure difference is caused by the combined effect of naturally and mechanically induced driving forces. Of particular importance are joints between different building components and the fixing of different installations.

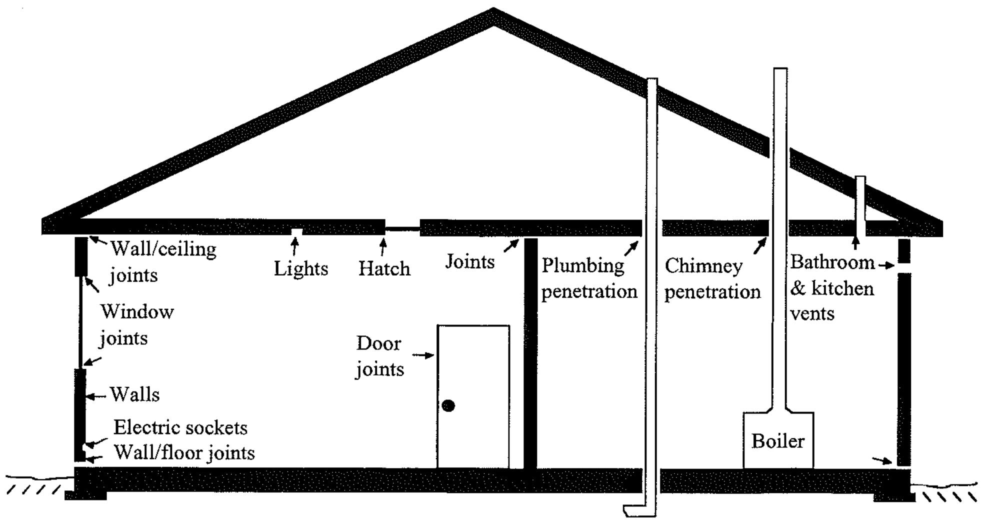


Figure 2.1. Typical air leakage paths in a house [Awbi 1991]

The degree of envelope air tightness, the size and distribution of the leaks on the building, the indoor-outdoor pressure difference, and the climatic conditions determine the rate of uncontrolled air exchange in buildings. Typical air leakage paths in a building are illustrated in Figure 2.1. Determination of the airflow through the envelope requires a knowledge of the above mentioned influencing factors. The main concept of estimating the quantity of uncontrolled air leakage is based on the mass balance of inflow and outflow air across the whole building envelope through large and small openings (cracks).

2.1.1 Air exchange through large openings

For an opening of relatively large free area, such as a vent or a large crack, the flow tends to be approximately turbulent under normal pressures [Awbi 1991]. In this case the flow rate, Q, is proportional to the square root of the pressure difference across the envelope and can be evaluated using the standard orifice flow equation:

$$Q = C_d A \cdot \left(\frac{2\Delta p}{\rho} \right)^{0.5}, \ \mathrm{m^3 s^{-1}} \tag{2.1}$$

Where,

C_d	=	discharge coefficient of an opening
A	=	flow area, m^2
Δp	=	pressure difference across opening, Pa
ρ	=	air density, kg/m^3

In sharp-edge orifice flow, the discharge coefficient is almost dependent of the Reynolds number and has a value of 0.61. However, according to [Etheridge, 1977] this constancy is not observed for most building openings because of the geometry of the openings and the variation in pressure difference with the environmental conditions inside and outside the building. BS 5925 [1980] recommends using equation (2.1) for openings of typical dimensions larger than approximately 10mm. The effective leakage area, C_dA, can be determined by means of a building pressurisation or depressurisation test or may be taken from tables given in the ASHRAE Handbook [1989] for different building components.

2.1.2 Air exchange through small openings

For very narrow cracks with deep flow paths (such as mortar joints and tight-fitting components) the flow within the openings is essentially laminar or viscous. In such cases the airflow rate is given by the Couette flow equation:

$$Q = \left[\frac{bh^3}{12\mu L} \right] \Delta p, \ \mathrm{m^3 s^{-1}} \tag{2.2}$$

Where,

b	=	length of crack, m
h	=	height of crack, m
L	=	depth of crack in flow direction, m
μ	=	absolute viscosity of air, Pa s

For wider cracks the airflow is usually neither laminar nor fully turbulent but in the transition region. A combination of equation (2.1) and (2.2) is therefore used to form a single power equation of the form:

$$Q = kL(\Delta p)^n, \ \mathrm{m^3\ s^{-1}} \tag{2.3}$$

Where,

k = flow coefficient, $m^3\ s^{-1}\ Pa^{-1}$
L = length of crack, m
n = flow exponent

This is normally referred to as the crack flow equation in which k is a function of the crack geometry and n is dependent on the type/nature of the flow and acquires a value of 0.5 for fully turbulent flow and 1.0 for laminar flow. In practice the value for n for cracks or adventitious opening tends to range between 0.6 and 0.7. A range of values of k for cracks formed around closed windows are given in BS 5925 [1980]. These should be used with a value of n = 0.67. Because equation (2.3) is not dimensionally homogeneous it lacks generality of application Awbi [1991]. Thomas *et al* [1953] suggested that a quadratic form of equation (2.3) that is dimensionally homogeneous be used as it provides more accurate assessment of the flow through a crack. This equation has the form:

$$\Delta p = aQ^2 + bQ \tag{2.4}$$

Where a and b are parameters for the general leakage function. The first term on the right-hand side of equation (2.4) represents turbulent flow and the second represents laminar flows. The later becomes significant at low flow rates and the former is more significant at larger flow rates. The values for a and b can be obtained from experimental tests on the openings and values for some openings can be found in Backer *et al* [1987]. Comparison of the air infiltration rates predicted by the power-law and quadratic equation with measurements in a family dwelling by Liddament [1987] showed that the two equations produced identical results for large pressure differences (Δp > 20 Pa). However, the power-law was superior at low-pressure differences, i.e. of the order existing under normal environmental conditions. Nevertheless, in comparisons made by [Baker *et al*, 1987], it was discovered that the nature of the flow and the effect of dynamic pressure coefficients of leakage paths are taken into account a bit better by equation (2.4)

2.2 Air leakage measurements

Air leakage is caused by the interaction of envelope tightness with the driving forces such as wind and buoyancy or stack effect. Air leakage measurements provide the knowledge about the air tightness of building envelopes and airflow in buildings. They are necessary for commissioning, design, diagnostic analysis and research. Several techniques are available with each having a specific purpose. Popular methods include tracer gas techniques for evaluating ventilation flow rates in buildings and pressurisation testing to determine the air tightness of buildings or building components. In addition, a wide range of other methods is available to measure and visualise airflows in buildings. A detailed information regarding measurement methods is given in a work by Roulet *et al* [1991]. In the present study, tracer gas and pressurisation methods were used for air leakage measurements.

2.2.1 Tracer gas methods

Tracer gas is used to measure air flow through many unknown cracks, holes, and gaps that may be present within the building envelope or the air flow rate through more than two purpose provided openings at the same time. The technique is performed by releasing an inert gas into a space where its concentration is monitored as it mixes with the fresh incoming air. The air flow rate into and/or from the building (zone) is evaluated by measuring either the variation in tracer gas concentration over time or the rate at which tracer gas needs to be released to maintain a target concentration in the room. Depending on a specific application, several tracer gas techniques can be used which include:

- Concentration decay
- Constant concentration
- Constant emission
- Long term average
- Multi-tracer analysis
- Inlet pulse technique
- Homogeneous pulse technique

Measurements may be instantaneous, representing ambient conditions, or time averaged, in which the measurement period may take several days or weeks. A comprehensive information concerning the above mentioned techniques can be found in [Liddament 1996]. In the present study, uncontrolled air leakage in the test buildings was carried out by using concentration decay technique.

2.2.2 Pressurisation method

Pressurisation/depressurisation tests provide valuable information concerning the air leakage characteristics of a building envelope. The method consists of mechanical pressurisation or depressurisation of a building and measuring the resulting air flow rates at a given internal-external static pressure difference. It provides only information regarding the air tightness of a building due to imperfections and is usually expressed in terms of the number of air changes per hour (ach) at 50 Pa pressure difference. For large buildings where such a large value of pressure difference cannot easily be achieved, a value of Δp = 25 Pa is sometimes used [Charlesworth, 1988]. Detailed information concerning this technique can be found in [Charlesworth 1988 and Sherman *et al* 1980].

While pressurisation could be used to measure air tightness of different buildings, the obtained data doesn't give a direct estimate of the real-time air leakage under natural conditions. The method provides no information on the distribution of openings or on how winds, temperature, topography, or shielding will affect infiltration. However, based on pressurisation data, valuable information concerning the average air leakage performance of a building can be obtained. Numerous experimental tests have shown that the approximate number of uncontrolled seasonal air change can be obtained through equation (2.5) [Liddament 1996, Sherman *et al* 1998].

$$ACH \approx \frac{ACH_{50}}{20} \tag{2.5}$$

Where ACH is the natural uncontrolled air changes per hour and ACH_{50} are the air changes induced by a 50 Pa pressure difference using a fan. Should the pressurisation test data be available, equation (2.5) provides a useful "rule of thumb" [Kronvall 1978] for estimating air infiltration rate due to natural conditions. It is of value when considering the implication of building air tightness on the design performance of ventilation systems and heating energy consumption of buildings. For example, a mechanically ventilated building would need a considerably greater degree of envelope air tightness if optimum performance of the system and energy losses due to air infiltration were to be avoided. The number 20, is an empirical coefficient representing the average influence of driving forces and surrounding shielding. According to Dubrul [1988], this value may be varied from between 10 and 30 to account for the building size and the degree of shelter.

2.3 Pressures due to wind

Wind creates a pressure over the outer surfaces of a building. This pressure, in combination with the stack effect and the operation of mechanical ventilation systems forms the driving force for air leakage. Wind pressure distribution on a building depends on many factors such as wind speed, wind direction, topography, building geometry and orientation. The changing nature of wind speed and direction causes fluctuations in pressure distribution over a building surface. Wind velocity increases with height; hence, greater wind speeds have to be used when considering the pressures acting on buildings with heights greater than 10m. Wind pressure tends to be greatest near the centre of the windward face with most severe suction at the edges and corners of a building. Relative to the static pressure of wind, the time mean pressure due to wind velocity acting at any point on the surface of a building can be determined by using Bernoulli's equation:

$$P_w = \frac{1}{2} C_p . \rho . \upsilon_i^{\,2} \text{, Pa} \tag{2.6}$$

Where,

P_w = Pressure due to wind over a surface, Pa
C_p = Wind pressure coefficient over a surface
ρ = Air density, (1.2 kg/m^3)
υ = Wind speed, ms^{-1}

Figure 2.2 shows the pressure distribution over a surface of a building due to wind. It was assumed that infiltration occurs through the walls against the windward while exfiltration occurs through the leeward and side-walls. The inflow air is also assumed to be equal to the outflow air.

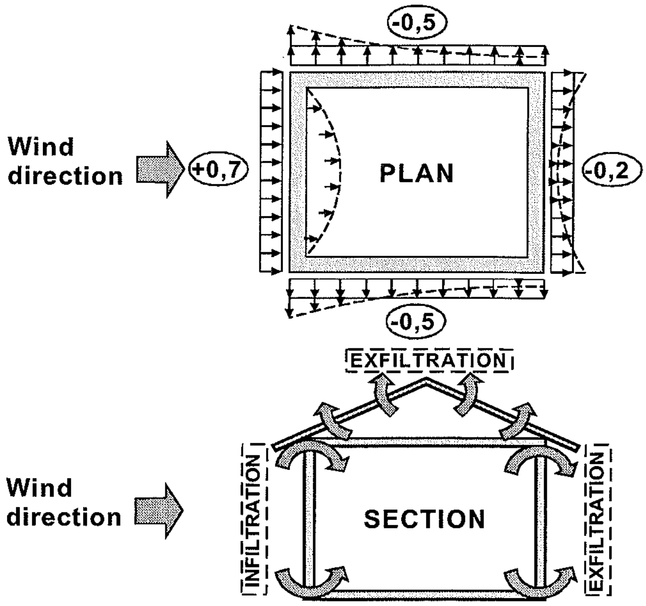


Figure 2.2. Wind pressure distribution over a building envelope and the resulting air infiltration/exfiltration.

The wind pressure coefficient, C_p, is normally derived from pressure measurements in wind tunnels using building models or building component models or pressure measurements in actual buildings. Values of C_p vary from 0.5 to 0.8 on the windward face, while on the leeward side they vary from –0.3 to –0.4 [Markus *et al* 1980]. More wind pressure data may be obtained from [Lidddament 1986, BS 1972].

2.4 Stack effect (buoyancy) and impact of leakage through the roof

The indoor-outdoor temperature difference causes differences in density between air inside and outside the building resulting into the so-called *stack effect*. The variation of air density with temperature produces pressure gradients both within the internal and external zones of a building. This pressure difference varies linearly with height and the level where the pressure inside and outside are equal is called the neutral pressure axis, Figure 2.3. Transition between inflow and outflow air occurs at this axis. In practice, the position of neutral pressure axis is a function of the overall leakage distribution and flow characteristics of all openings within the building envelope, which is seldom known. However, if the leakage paths and openings are uniformly distributed over the envelope, the neutral pressure level will occur at the mid-height of the building.

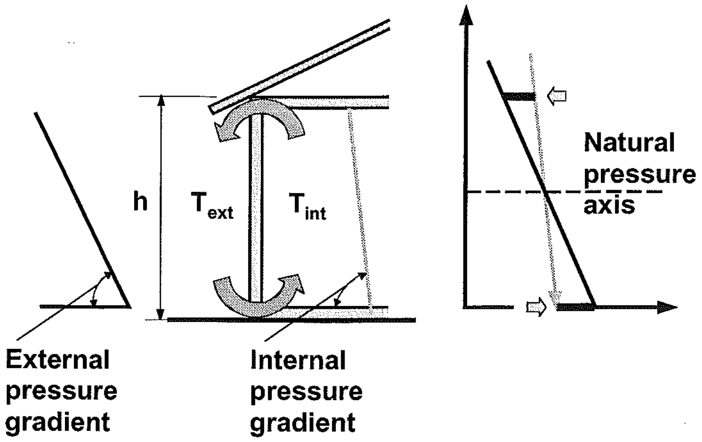


Figure 2.3: Internal-external pressure gradient and the position of the neutral pressure axis

In winter, when inside air temperature is greater than that outside, colder outside air infiltrates into the building through cracks and openings at the lower part of the building and warm inside air ex-filtrates through cracks and openings at higher levels above the neutral pressure axis. A reversal of this flow direction occurs during the cooling season when the inside air temperature is lower than that outside. The pressure due to stack effect is given by expression:

$$P_h = P_o - \rho g h \tag{2.7}$$

Where

P_h	=	static pressure at height h, Pa
P_o	=	static pressure at height 0, Pa
ρ	=	air density, kg m^{-3}
g	=	gravitational acceleration, m s^{-2}
h	=	height measured from datum, m

The vertical pressure gradient due to stack effect, Δp_{stack}, is given by:

$$\Delta p_{stack} = -\rho_i g \Delta h \frac{T_i - T_e}{T_e}, \text{ Pa} \tag{2.8}$$

Where,

ρ_i	=	density of air in a building, kg m^{-3}
Δh	=	vertical distance from neutral pressure axis, up being positive, m
T_i	=	internal air temperature, K
T_e	=	external air temperature, K

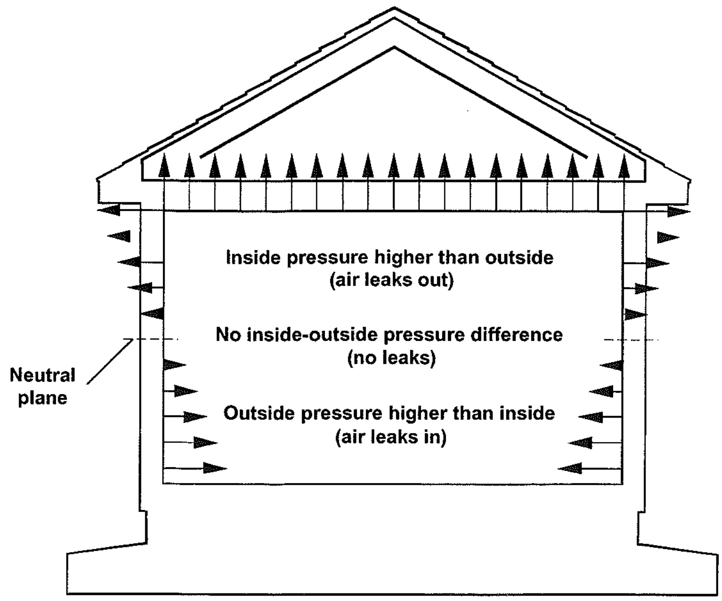


Figure 2.4: Air leakage due to stack effect during heating season [Kreider et al 1994].

The stack effect tends to be relatively small in low-rise buildings; up to about five floors, but in high rise building it can dominate and should be given a close attention. Large pressure differences due to stack effects in high-rise buildings can be minimised through a proper control, from floor to floor. In low-rise buildings however, if air leakage through the roof is present, refer to Figure 2.4, the stack effect can cause a tremendous impact on heating energy. The effect of air leakage though the roof to heating energy consumption has been reported in a work by [Jokinen 1998].

In buildings with mechanical ventilation, there will be a pressure difference, Δp_{vent}, caused by the ventilation system if the supply and exhaust airflow is not balanced. The resulting pressure difference, Δp_{vent}, depends on the air tightness of the building envelope and the design and operation of the ventilation system. In addition, there is some coupling to wind and the stack effect. Therefore the determination of pressure difference due to the ventilation system might be difficult. However, the situation is simple if Δp_{vent}. is larger in magnitude than the pressure difference created by wind and stack effect. It is important to note, however, that some designers recommend a slight depressurisation of residential buildings in order to prevent moisture migration into the building fabric. Hence, if the building is depressurised to Δp_{vent}, by mechanical ventilation and if wind and stack pressures are smaller than Δp_{vent}, then it is indeed fair approximation to neglect them all together [Kreider *et al* 1994].

3. RESEARCH APPROACH AND METHODS

The research comprised of both theoretical and experimental parts. Current theories and practices on building ventilation, building air tightness, ventilation systems, ventilation heat recovery, energy impact of ventilation and infiltration, wind pressures on low-rise buildings, and heating energy consumption in buildings were reviewed. Theoretical prediction of the quantity infiltration air in buildings due to pressure differences resulting from various wind speeds was carried out.

Activities that were performed in the experimental part involved the following:

1. Determination of the air tightness of the three test buildings (pressurisation method)
2. Determination of the quantity of uncontrolled air leakage (tracer gas method)
3. Installation of MVHR systems into the three test buildings and taking measurements
4. Data collection, calculation of the heating degree-days, and calculation of heating energy losses taking into account the energy recovered.

3.1 Description of the test buildings

The tests were carried out in three of six test buildings constructed in a moderately exposed parking area within the compound of Tampere University of Technology. Table 3.1 shows the characteristics of each building.

Table 3.1: Characteristics of the three test buildings

Test building number	Materials for the external walls	U-values (W/m².K)	
		Roofs & Floors	**External walls**
1	Polyurethane insulated wooden frame wall	0.19	0.17
3	Insulated log wall	0.19	0.29
5	Autoclaved aerated concrete block wall	0.19	0.35

The floor area of each test building was 2,4 x 2,4 m^2 and the free floor to ceiling height was 2,6 m. Both the ceiling and the floor consisted of two layers of foamed polyurethane elements with overall thickness of 200 mm. All the buildings had two well-insulated outer doors fixed one after another. The buildings had no windows.

The buildings were heated by using electric radiators. Additional heat in the indoor air was obtained from the control and monitoring equipment such as computers etc. During the tests the indoor air temperature was maintained constant at 20°C ± 1°C. Balanced mechanical ventilation systems with air-to-air heat recovery, (PARMAIR IIWARI Ex S) were used to ventilate the three test buildings. The systems' technical specifications are shown in appendix 6. Full details of the tested ventilation systems can be obtained from the manufacturer. The air change rates in the buildings were set at 0.5 h^{-1}, slightly higher compared to the outdoor air change requirement for residential buildings in ASHRAE Standard [62-1989] of 0.35 h^{-1}. The exhaust and supply air flows were slightly unbalanced (supply air flow was approx. 0.8 of the exhaust air flow). The air ducts/pipes were insulated by 100-mm mineral wool. Water vapour was produced by continuously heating water that was kept in a container inside each building to provide additional moisture content in the indoor air of 2 g/m^3 for occupancy simulation. The indoor RH varied between 25.27 and 45.21 % depending on the moisture content in the outdoor air.

3.2 Measurements

3.2.1 Infiltration air change rates

Infiltration air change rates of the test buildings were measured by using tracer gas technique (decay method). Tracer gas (CO_2) was injected into the buildings until a 4-g/m^3-concentration level was achieved. As no further tracer gas (CO_2) was released into the room after achieving this concentration level, its concentration decayed as air infiltration/exfiltration took place with time. This concentration decay of the CO_2 was automatically monitored over a period of 3 to 4 days until it reached 0 g/m^3. The average air infiltration/exfiltration flow rates $\overline{Q}$ (h^{-1}) were then calculated by using equation 3.1. [Etheridge, 1996].

$$\overline{Q} = V \frac{\ln \frac{C(t_1)}{C(t_2)}}{t_2 - t_1}, \text{ h}^{-1} \tag{3.1}$$

Where, V is the volume of the ventilated space in m^3, $C(t_1)$ and $C(t_2)$ are the percentage concentrations of the gas at time t_1 and t_2 in hours respectively.

3.2.2 Air tightness of the test buildings

The air tightness of the test buildings was measured by using fan pressurisation method. This is the most common method used for measuring the global air tightness of a building envelope. A simplified form of the measurement principle is shown in Fig. 3.1. Normally, a fan powerful enough to create up to 100 Pa pressure difference over the building envelope is mounted in a door or window opening. By using the fan, air is sucked from the building while recording the airflow through the fan for each incremental step from ±10 to ±100 Pa. In the present study, a fan mounted to a pipe that was fixed through the wall to the inside was used to depressurise the building. For each pressure increment, the corresponding air flow rate through the fan was measured. The relationship between induced pressure and air flow rate was then plotted from which the air tightness of the building was determined. To minimise the effect of naturally developed pressures, the test was carried under low wind speed conditions.

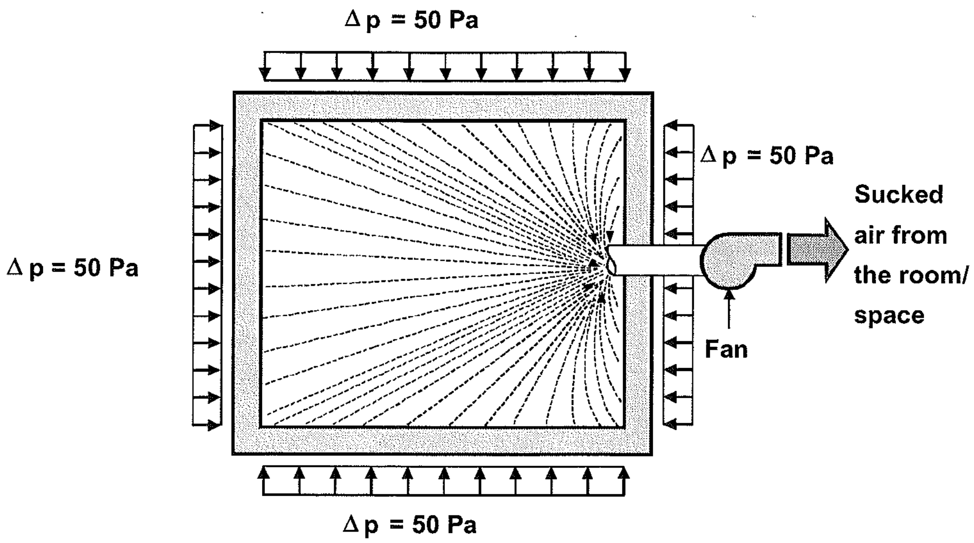


Figure 3.1: Building air tightness measurement (depressurisation method)

Flow rate through the fan was measured with a calibrated orifice plate where as the pressure difference was measured with a manometer, which was connected to the pressure taps. The method is fairly simple to use especially for detached single-family houses. Also the method is suitable for controlling building air tightness by local building inspectors. It can also be used for measuring individual apartments in multi-family houses. Before the tests, all the purposely provided openings within the buildings including the supply and extract air pipes were sealed by tapes. The air tightness of the test buildings was determined at a 50 Pa pressure difference. The Swedish Code of Practice [1988] gives recommendations regarding the level of air tightness. For detached single-unit dwellings and linked houses an air tightness equivalent to an hourly leakage of three times the building's volume (3 ach), at a pressure difference of 50 Pa is considered reasonable [Gusten 1989]. Pressurisation testing is also sometimes carried out in case of verification of air tightness regulations or standards; assessing air tightness retrofit needs; and estimating air infiltration risks. Results obtained from the pressurisation tests at a 50 Pa pressure differences are shown in Table 3.2.

Table 3.2: Air change rates at 50 Pa pressure difference for the three test buildings

Building No. (type)	Volume [m^3]	Walls area [m^2]	Air change rate at n_{50} [h^{-1}]
1 (Polyurethane insulated frame wall)	15	25	0.93
3 (Insulated log wall)	15	25	11.1
5 (Autoclaved aerated concrete block wall)	15	25	1.2

For buildings which are very leaky, it may sometimes be impossible to achieve a 50 Pa pressure difference during the pressurisation test, especially if the fan used is not very powerful. In such cases interpolation can be made between two known air change rates at lower pressure differences or equation (3.2) [Nevander *et al* 1994] can be used. Equation (3.2) was used to determine the number of air changes at p = 50 Pa for the insulated log wall test building (Bldg. No. 3).

$$n = n_{50} \cdot \left(\frac{\Delta p}{50} \right)^{\beta} \tag{3.2}$$

Where,

n = the number of air changes per hour at a given pressure difference, h^{-1}
n_{50} = the number of air changes per hour at 50 Pa pressure difference, h^{-1}
Δp = pressure difference, Pa
β = the pressure coefficient, normally taken as equal to 0.7

Figure 3.2 depicts the number of air changes per hour, *n*, for various pressure differences for the three test buildings as calculated by using expression (3.2). These results compares very well with those obtained through measurements for the test building number 1 and 5.

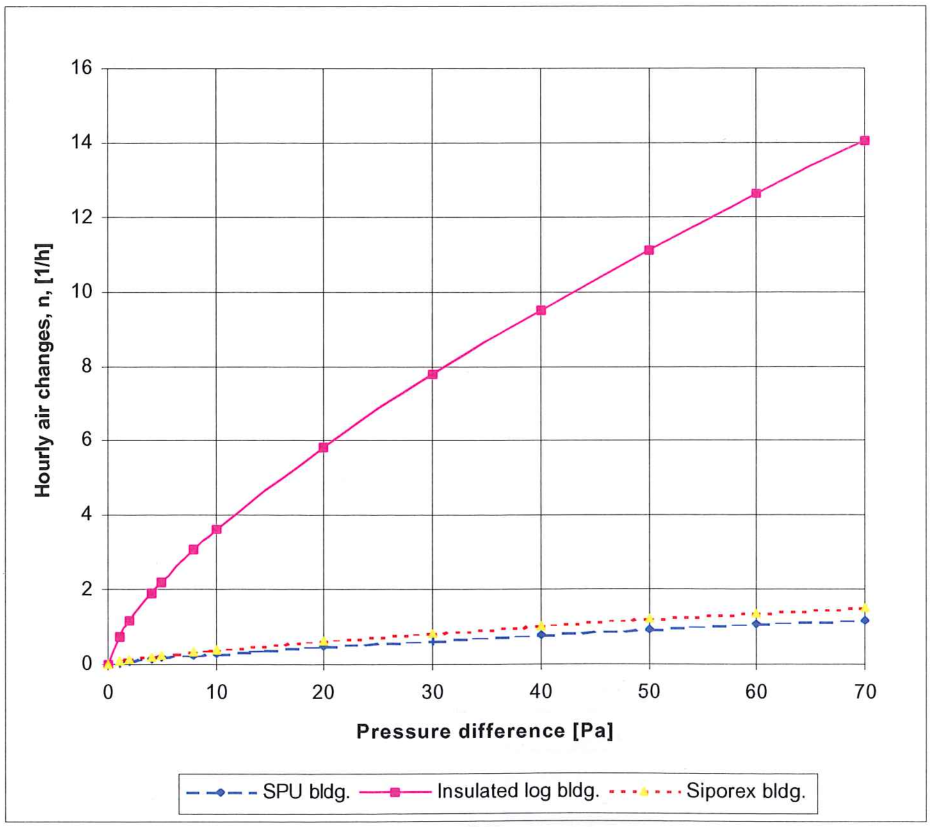


Figure 3.2: The number of air changes per hour 'n' at various pressure differences.

3.2.3 Wind speed and direction

In determining the uncontrolled air change rates (infiltration/exfiltration) it is important to have knowledge about the climate of the locality in which the building is situated. Of the important parameters, wind speed and direction is one of the primary parameters of concern. The air flow around a building and the resulting pressures depend on the design and orientation of the building, the wind speed and direction, as well as the influence of the surrounding buildings, vegetation and topography.

The actual wind speed and its direction relative to a building creates a certain pressure distribution over the building, which causes air leakage through the holes, cracks, joints, gaps etc. within the envelope. For the present study, the wind speed and direction was measured on site where the test buildings are located. The measurements were taken at a 10-m height from the earth surface by using a wind speed meter that was fixed on a steel mast at building No. 2. A 3-cup anemometer was used to measure the wind speed whilst the wind direction was defined by using a wind streamer.

The percentage distribution of wind speeds, including their maximum and average values under the period 1961-1980 for Tampere during different seasons of the year were obtained from [RT 05- 10390]. These values are presented in Table 3.3 below.

Table 3.3: Percentage distribution of wind speeds, including their maximum and average values under the period 1961-1980 for Tampere

Place - Tampere	Wind speeds [m/s]							
	Calm	**1**	**2-3**	**4 - 5**	**6 - 8**	**9**	**Max.**	**Average**
Whole year	10.4	9.4	34.7	31.0	13.4	1.1	14	3.3
Winter	11.8	9.5	33.8	28.4	14.7	1.8	13	3.3
Spring	12.7	9.7	33.3	29.8	13.5	1.0	12	3.3
Summer	10.2	10.4	38.9	30.6	9.4	0.5	11	3.1
Autumn	7.0	8.2	32.5	35.4	16.1	0.8	14	3.6

By using the data presented in Table 3.3 together with the data for the mean outdoor temperatures during different seasons, also for Tampere that was obtained from RT 05-10426, (Ilmasto, lämpötilö) Table 3.4 was made.

Table 3.4: Wind speeds, their duration, and the mean outdoor temperatures during different seasons for Tampere

SEASONS		Wind speeds, υ_i (m/s)								Mean outdoor temp. (°C)
		0	1	2-3	4-5	6-8	≥ 9	Aver.	Max.	
WINTER	Duration, t_i(h)	254.88	205.2	730.08	613.44	317.52	38.88	3.3	13	-6.5
	%	11.8	9.5	33.8	28.4	14.7	1.8			
SPRING	Duration, t_i(h)	280.42	214.18	735.26	657.98	298.08	22.08	3.3	12	1.3
	%	12.7	9.7	33.3	29.8	13.5	1.0			
SUMMER	Duration, t_i(h)	225.22	229.63	858.91	675.65	207.55	11.04	3.1	11	15
	%	10.2	10.4	38.9	30.6	9.4	0.5			
AUTUMN	Duration, t_i(h)	152.88	179.09	709.80	773.14	351.62	17.47	3.6	14	3.6
	%	7.0	8.2	32.5	35.4	16.1	0.8			

Table 3.4 was made so that it could be used in conjunction with the formula that was derived in this study (see section 3.5) to estimate both the seasonal and annual heating energy consumption due to infiltration air caused by natural conditions. The table was made by multiplying the number of days in each season by twenty-four in order to obtain the number of hours in each season. Then the obtained number of hour was multiplied by the percentage of time duration for every wind speed category to obtain the number of hours during which they lasted. The seasonal average outdoor temperature is the mean value of the minimum temperatures in each of the three months in a particular season.

3.2.4 Indoor and outdoor temperatures

The indoor air temperature was monitored at three levels inside the buildings: near the floor, in the mid-height, and near the ceiling. The average value among the three measurements was taken as the indoor temperature. Exterior temperatures were monitored over the roof, under the floor, and on the exterior wall surfaces. The supply air temperature was monitored at two points before entering the heat exchanger and at one point when it leaves the heat exchanger and before entering the room. Similarly, the extract air temperature was monitored at two points just as it leaves the heat exchanger and before being sent outside the buildings. The temperatures were measured by using calibrated semiconductor sensors (T-type) and cooper-constantan thermocouples (Cu-Ko, Cu-CuNi). The data from the sensors was collected by the help of multiplexers in such a way that data transmission from each channel took place after every 20 seconds to the computer using ADDA cards for analog to digital data conversion. The measured minimum, maximum, and the average values were automatically saved to a computer hard disk after every 30 minutes. The on site measured values for monthly mean outside temperatures is shown in Table 3.5.

Table 3.5: Measured monthly mean outside temperatures for Tampere, 1999/2000

Month	Outside temperatures (°C)		
	Minimum	Mean	Maximum
September '99	-0.43	11.20	24.05
October '99	-3.70	4.06	13.86
November '99	-5.79	3.29	10.38
December '99	-14.62	-2.97	21.24
January '00	-20.54	-4.13	-0.05
February '00	-19.29	-4.28	2.25
March '00	-12.04	-1.90	9.96
April '00	-8.40	3.99	17.64
May '00	-3.72	9.65	22.62

3.3 Derivation of an equation for predicting the uncontrolled air change rates per square meter of a wall at various pressure differences based on pressurisation test data

If the number of air changes per hour at 50 Pa pressure difference, (n_{50}), is known, the quantity of air leakage per square meter of a wall in one hour, ($m^3/m^2.h$), can be predicted by using the expression:

$$R_{50} = n_{50} \cdot \frac{V}{A_{tot}} \tag{3.2}$$

The infiltration air change rate through walls at a given pressure difference, (Δp), can be determined by using the formula:

$$R = R_{50} \cdot \left(\frac{\Delta p}{50} \right)^{0.7} \tag{3.3}$$

Substituting (3.2) into (3.3) we obtain,

$$R = \frac{V}{A_{tot}}.n_{50}.\left(\frac{\Delta p}{50}\right)^{0.7} \tag{3.4}$$

Where,

R = Infiltration air change rate at a given pressure difference, $m^3.m^{-2}.h^{-1}$
V = Volume of the building, m^3
A_{tot} = Total area of the leaking surfaces/walls, m^2
Δp = Any given pressure difference, Pa

3.4 Derivation of an equation for estimating the quantity of uncontrolled air change rate due to wind

The calculation of air exchange rate due to wind requires information about wind pressure distribution over the building surface with its positive and negative parts, the magnitude of the external pressures, and the distribution of leakage paths. However, it is difficult to establish the exact relation between the registered air change, wind speed, and the outdoor temperature in practice. In the present study, the air exchange due to wind was calculated based on equality between the airflow volumes into and from a building as shown in equation (3.5) [Gusten 1989]:

$$\int_{A_i} dQ = -\int_{A_u} dQ \text{, } m^3h^{-1} \tag{3.5}$$

Where,

A_i = The surface area of the building envelope, through which air flows into the building
A_u = The surface area of the building envelope, through which air flows out from the building
dQ = The volume of air flowing in or out through a surface unit, taking the air temperature into consideration

Assuming that wind creates a pressure difference, P_w, over the building envelope, infiltration air change due to wind can be calculated by using the expression:

$$R_w = n_{50}.\frac{V}{A_{tot}}\left(\frac{P_w}{50}\right)^{0.7} \text{, } m^3.m^{-2}.h^{-1} \tag{3.6}$$

Furthermore, we can assume that infiltration due to wind occurs only through the windward wall and exfiltration through the rest three walls. The number of air changes per hour in a building due to wind will hence be given by the expression:

$$n_w = \frac{R_w.A_1}{V}, \text{ h}^{-1} \tag{3.7}$$

Substituting (3.6) into (3.7) gives,

$$n_w = n_{50}.\frac{V}{A_{tot}}.\frac{A_1}{V}\left(\frac{P_w}{50}\right)^{0.7}, \text{ h}^{-1} \tag{3.8}$$

Substituting (2.6) into (3.8) we obtain,

$$n_w = n_{50}.\frac{A_1}{A_{tot}}.\left(\frac{\frac{1}{2}C_p.\rho.v_i^2}{50}\right)^{0.7}, \text{ h}^{-1} \tag{3.9}$$

Where,

n_w	=	The hourly number of air changes due to wind pressures, h^{-1}
n_{50}	=	The hourly number of air changes at 50 Pa pressure difference, h^{-1}
A_1	=	Area of the wall against the wind direction (windward wall), m^2
A_{tot}	=	Total area of all leaking surfaces (in our case – four walls), m^2

An alternative method for calculating the additional air flow rate, $\dot{V}_x$, induced by wind and stack effect for leaky envelopes of buildings ventilated by mechanical ventilation systems is given in [CEN/TC89/WG4 N 174]. This additional air flow rate $\dot{V}_x$ can be calculated from equation (3.10):

$$\dot{V}_x = \frac{Vn_{50}e}{1+\frac{f}{e}\left[+\frac{\dot{V}_S-\dot{V}_E}{Vn_{50}}\right]^2} \tag{3.10}$$

Table 3.6: Shielding coefficients, "e" and f, for calculation of additional air flow rate according to equation (3.10) [CEN/TC89/WG4 N 174]

COEFFICIENT "*e*" FOR SHIELDING CLASS:	**More than one façade exposed**	**One façade exposed**
No shielding: buildings in open country, high rise buildings in city centres	0.10	0.03
Moderate shielding: buildings in the country with trees or other buildings around them, suburbs.	0.07	0.02
Heavy shielding: buildings of average height in the city centres, buildings in forests	0.04	0.01
COEFFICIENT "*f*":	15	20

Where,

n_{50}	=	The air change rate from a pressure difference of 50 Pa between inside and outside, including the effects of air inlets
e and f	=	Shielding coefficients as given in Table 3.6

3.5 Derivation of an equation for estimating the annual heating energy consumption due to infiltration air caused by winds

Infiltration air change rate across walls of a building at a certain pressure difference, Δp, is given by equation (3.3) above. Taking Δp as the pressure created by the wind (Eqn. 2.10) and substituting it into equation (3.3) we obtain:

$$R = R_{50}.\left(\frac{\frac{1}{2}c_p.\rho.v^2}{50}\right)^{0.7}, \; m^3m^{-2}.h^{-1} \tag{3.10}$$

Substituting 0.7 and 1.2 (kg/m^3) into equation (3.10) as the values of the wind pressure coefficient over a surface, c_p, and the density of air, ρ, respectively, we obtain:

$$R = R_{50}.\left(0.0084.v^2\right)^{0.7} \tag{3.11}$$

Substituting equation (3.2) into (3.11) gives,

$$R = n_{50}\frac{V}{A_{tot}}.\left(0.0084.v^2\right)^{0.7} \tag{3.12}$$

The volumetric air change rate in a building, $\dot{V}$, is given by the expression:

$$\dot{V} = R.A_1 \tag{3.13}$$

Where, A_1 is the area of the wall on the windward side, which equals to $A_{tot}/4$ for a building having a square plan. Substituting equation (3.12) into (3.13) we obtain:

$$\dot{V} = n_{50}.\frac{V}{A_{tot}}\left(0{,}0084.v^2\right)^{0.7}.\frac{A_{tot}}{4} \tag{3.14}$$

The number of infiltration air changes per hour due to wind, n, is therefore given by the expression:

$$n = \frac{V}{V} = n_{50} \cdot \frac{V}{4} \left(0{,}0084.v^2\right)^{0.7} \cdot \frac{1}{V} \tag{3.15}$$

By rearranging equation (3.15) we get,

$$n = n_{50} \cdot \frac{1}{4} \left(0{,}0084.v^2\right)^{0.7} \tag{3.16}$$

Where, v stands for wind velocity/speed in meters per second.

Equation (3.16) gives the number of air changes per hour when a wind of velocity v acts over a building. The volume of infiltration air, which results from wind speed v_i acting over a building surface can be calculated by using the expression:

$$V_{\inf} = \frac{1}{4}.V_B.n_{50}.\left(0{,}0084.v_i^{\,2}\right)^{0.7}.t_{i(s)} \tag{3.17}$$

Where,

V_B = Volume of the building in question
$t_{i(s)}$ = Time duration for wind 'i' during a particular season 's'

The quantity of energy 'E' that will be needed to heat the infiltrating air caused by wind is given by the formula:

$$E = \rho.C_p.\Delta T_i.V_{\inf} \tag{3.18}$$

Substituting (3.17) into (3.18) together with the specific heat capacity of air, C_p, (1.0 kJ/kg.°C) and the air density, ρ, (1.2 kg/m^3) values we obtain:

$$E = 1{,}057.10^{-2}.\Delta T_i.V_B.n_{50}\left(v_i\right)^{1.4}.t_{i(s)} \tag{3.19}$$

The annual energy consumption for heating infiltration air that is caused by wind can be calculated by using the formula:

$$E = 1{,}057.10^{-2}.V_B.n_{50}.\sum_{i=1}^{n}\left[\Delta T_i.t_{i(s)}.(v_i)^{1.4}\right] \tag{3.20}$$

Where,

V_B = Volume of a building, (m^3)
n_{50} = The number of hourly air changes at 50 Pa pressure difference, (h^{-1})
ΔT_i = Temperature difference between the indoor air and the mean seasonal outdoor temperature, (°C)
$t_{I(s)}$ = Duration of time for wind 'i' during a particular season, 's' (h)
υ_i = Different wind speeds in different seasons of the year, (m/s)

4. CALCULATIONS

4.1 Heating degree-days

Heating degree-days (degree-hours) is a function of the base temperature, reflecting the role of indoor temperature, incidental/free heat gain, and the heat loss coefficient of the envelope. It is based on the period (duration) during which the outdoor temperature is less than a specified base temperature (T_b). It is given by the sum of the differences between the base temperature and each hourly average outdoor temperature, (T_o), throughout the heating season for which (T_o) is less than (T_b). The obtained sum is known as the heating degree-hours. The number of heating degree-days is obtained by dividing the sum by 24. In this particular study, the number of heating degree-days was determined by summing up the differences between the base temperature and the measured hourly average outdoor temperature as per equation (4.1). The base temperature used was 17 °C for Finland [RT 05- 10426, 1990]

$$D_h = \sum_{i=1}^{n} (T_b - T_o), \text{ for } T_b > T_o \tag{4.1}$$

Where D_h is the heating degree-hours (K) and n is the total number of hours over the whole heating and ventilating period.

When data for hourly average outdoor temperature is not available, other formulas proposed by several authors can be used for estimating the degree-days relative to an arbitrary base temperature. The idea is based on assumption of a typical probability distribution of temperature data, characterised by its monthly mean outdoor temperature, $\bar{T}_o$, and by its standard deviation, σ. If the monthly mean outdoor temperature is known, the standard deviation for each month, σ_m, can be estimated from the correlation [Kreider, 1994]:

$$\sigma_m = 1.45 - 0.029\bar{T}_o + 0.0664\sigma_{yr} \text{ (dimensional equation., } T \text{ and } \sigma \text{ in °C)} \tag{4.2}$$

Where σ_{yr} is the standard deviation of the monthly mean temperatures, which is given by the expression:

$$\sigma_{yr} = \sqrt{\frac{1}{12}\sum_{n=1}^{12}\left(\bar{T}_o - \bar{T}_{o,yr}\right)^2} \tag{4.3}$$

about the annual average $\bar{T}_{o,yr}$. To obtain a simple expression for the degree-days, a normalised temperature variable θ can be used, which is defined as:

$$\theta = \frac{T_{bal} - \bar{T}_o}{\sigma_m \sqrt{N}} \tag{4.4}$$

Where N is the number of days in a month (N and θ are dimensionless). The mean monthly temperature $\bar{T}_o$ and its standard deviation account for the difference in temperature distribution from month to month and location to location. Being centred around $\bar{T}_o$ and scaled by σ_m, the quantity θ eliminates these effects. In terms of θ, the monthly heating degree-days for any location are very well approximated by the following distribution:

$$D_h(T_{bal}) = \sigma_m N^{3/2} \left\{ \frac{\theta}{2} + \frac{\ln[\exp(-a\theta) + \exp(a\theta)]}{2a} \right\} \tag{4.5}$$

Where a = 1.698. If one uses this equation for each month, the annual heating degree-days can be estimated with a maximum error of 175 °C [Kreider 1994].

4.2 Mechanical ventilation energy losses

Although the outdoor climate (temperature and wind) is normally well defined and information about buildings is largely available, the actual rate of air change that takes place in buildings is still not well predictable. As a result, it is somewhat difficult to make calculations of air change heating energy in buildings with a clear certainty. Due to this uncertainty, it is sometimes necessary to make assumptions about ventilation rates in order to estimate the air change heating energy. To estimate air change heating energy, the mass flow rate of air into and out of the building and the temperature difference between the incoming and outgoing air should be known.

In this study, direct measurements of indoor and outdoor thermal parameters were taken for each individual building. The mechanical ventilation air change rate in each building was 0.5 h^{-1} and a constant indoor temperature of 20 ± 1°C was maintained. The mechanical air change heating energy (E^h_{ach}) was calculated as for single zone in accordance with CEN/TC89/WG4 N 174 and the Finnish Building Code Part D5 [1985] by using two methods:

(i) Combining the hour by hour energy demand over the heating period, i.e.:

$$E^h{}_{ach} = \sum_{i=1}^{n} \{Q_{mv}.V.\rho.c_p.(T_{\text{int}(i)} - T_{ext(i)})\} / 3600 \tag{4.6}$$

Where,

n = The total number of hours of heating and ventilating, h

Q_{mv} = Mechanical ventilation design air change rate (0.5 h^{-1})
V = Volume of the ventilated building, m^3
$\tilde{n}$ = The air density (1.2 kg/m^3)
c_p = The specific heat capacity of air (1.0 kJ/kg.°C)
$T_{int(i)}$ = Indoor air temperature at hour, i, °C
$T_{ext(i)}$ = Outdoor air temperature at hour, i, °C

(ii) Heating degree-days method, in which the air change heating energy was determined by the expression:

$$E_{ach}^{h} = \left[24.D_d.\dot{Q}_{ach}V.\rho.c_p \right] / 3600 \qquad (4.7)$$

Where, D_d is the calculated heating degree-days, °C days.

4.3 Infiltration/exfiltration energy losses

The annual infiltration/exfiltration energy losses due to natural conditions were calculated by two different equations:

1) By using equation (3.20) that was deduced in the study. This equation took into account different seasonal wind speeds and the mean seasonal temperature data that are presented in Table 3.3.
2) By using the following equation (4.8) below

$$E_{\inf} = \rho.c_P.Q_{\inf}.V.\sum_{i=1}^{n}(T_{\text{int}} - T_{ext})/3600 \qquad (4.8)$$

Where,

E_{inf} = The heating energy loss due to air leakage, kWh
$\tilde{n}$ = The air density (1.2 kg/m^3)
c_p = The specific heat capacity of air (1.0 kJ/kg.°C)
Q_{inf} = Infiltration air change rate (h^{-1})
V = Volume of the ventilated building, m^3
n = The total number of hours of heating and ventilating, h
T_{int} = Indoor air temperature at hour, i, °C
T_{ext} = Outdoor air temperature at hour, i, °C

In the calculations for infiltration/exfiltration energy losses by using equation (4.8) above, the wind speed data that was measured on site was used.

4.4 Annual energy savings through ventilation heat recovery

The performance of a ventilation heat recovery is usually expressed in terms of percentage efficiencies of heat recovery (i.e. 60-70%) or coefficients of performance if a heat pump is incorporated. While these figures give an idea of how well the unit is performing, such efficiencies may not necessarily be achieved especially in leaky buildings when the total energy consumption of a building is considered. In this study, the energy recovery efficiency of the systems is treated in terms of the total ventilation energy input in a building. The energy recovered is considered entirely in terms of the sensible heat only. The recovery of latent heat by condensation in the exhaust air stream was not considered. Recovery of latent heat by condensation would be advantageous especially in very cold climate where heat exchangers have been implemented. However, it would be misleading to consider this as part of the general efficiency of the system, since moisture production generally occurs from cooking, bathing, or human perspiration, and so is not a charge on the space heating system of the house [McIntyre 1986]. The heat recovery efficiency of the ventilation systems that were used to ventilate the test buildings was calculated by using equation (4.9).

$$H_{eff} = \frac{T_2 - T_1}{T_3 - T_1} \tag{4.9}$$

Where,

T_1 = Supply air temperature before heat recovery, °C
T_2 = Supply air temperature after heat recovery, °C
T_3 = Extract air temperature before heat recovery, °C

The annual reduction in heating energy as a result of ventilation heat recovery was calculated by using the expression:

$$E_R = \rho . c_P . Q_{mv} . V . \sum_{i=1}^{n} \left(T_{after} - T_{before} \right) / 3600 \tag{4.10}$$

Where,

E_R = The heating energy recovered from the extract air, kWh
ñ = The air density (1.2 kg/m^3)
c_p = The specific heat capacity of air (1.0 kJ/kg.°C)
Q_{mv} = Mechanical ventilation design air change rate (0.5 h^{-1})
V = Volume of the ventilated building, m^3
n = The total number of hours of heating and ventilating, h
T_{after} = Temperatures of the supply air after being preheated as it passes through the heat exchanger, °C
T_{before} = Temperatures of the supply air before entering the heat exchanger for preheat, °C

4.5 Annual total ventilation energy input

In the context of the present study, the annual ventilation energy input is composed of energy consumption due to mechanical ventilation air change, infiltration energy losses, and energy used to operate the system (i.e. fan power). Energy expended for both humidification and dehumidification of the air was neglected. Thus the total ventilation energy was computed by using the expression:

$$E_{vent} = \left[Q_{\inf}.V + Q_{mv}.V\left(1 - \tfrac{H_{eff}}{100}\right)\right]\rho.c_p.\sum_{i=1}^{n}(T_{\text{int}} - T_{ext})/3600 + E_{syst} \quad (4.11)$$

Where,

Q_{inf} = Infiltration air change rate, h^{-1}

E_{syst} = Energy used to run the ventilation system, (approx. 325 kWh during the seven months of heating)

5. RESULTS AND DISCUSSIONS

5.1 Heating degree-days

The calculated heating degree-days results are shown in Table 5.1. These results have revealed that the heating degree-days could differ even for buildings, which are located in the same weather conditions. The differences observed in these results were mainly caused by the differences in internal temperatures within the three test buildings. The most important criteria for the accuracy of the heating degree-days method are that the indoor temperature within the building remains constant. When the indoor temperature is allowed to fluctuate, dynamic models should be used in the calculations of the heating energy consumption of a building.

Table 5.1: The number of heating degree-days for the three test buildings

MONTH	HEATING DEGREE-DAYS		
	Polyurethane Bldg. [No. 1]	**Insulated log** Building [No. 3]	Autoclaved aerated concrete [No. 5]
Nov ´99	418	468	386
Dec ´99	630	641	623
Jan ´00	600	599	608
Feb ´00	596	594	600
Mar ´00	536	536	541
Apr ´00	358	357	386
May ´00	203	198	237
Sum	3341	3392	3382

The Finnish Building Code of Practice (D5) [1985] offers an alternative formula for calculating the heating degree-days, as shown in equation (5.1).

$$S = (T_s - T_u).\ t \tag{5.1}$$

Where,

S = Heating degree-days
T_s = Indoor temperature, °C
T_u = Daily average outdoor temperature, °C
t = Calculation period, 24 hours

For this formula, the indoor temperature is used in the calculations instead of the base temperature. This may reduce the accuracy of the obtained results as the influence of wind speeds, solar radiation, and changes in microclimate are not taken into account. In other words, the thermal inertia of the building, which is taken into consideration when, defining the base temperature, will not be taken into consideration when indoor temperature is used instead of the base temperature. This may lead to a great source of error in the obtained results.

5.2 Mechanical ventilation energy losses

The calculated and measured results for mechanical ventilation energy losses are shown in Table 5.2. As anticipated, the mechanical ventilation energy losses in all the three test buildings is almost the same. This can be explained by the fact that the mechanical ventilation air change rate was 0.5 h^{-1} in all the buildings. The small differences however,

Table 5.2: Measured and calculated mechanical ventilation energy consumption in seven months

Building type	Air change heating energy [kWh]		
	Measured	**Calculated** (equation 5.2)	**Calculated** (equation. 5.3)
Polyurethane insulated wooden frame wall	322.5	252.0	200.5
Insulated log wall	269.6	253.6	203.5
Autoclaved aerated concrete block wall	279.6	240.8	202.9

may have resulted from the indoor temperature fluctuations within the test buildings. It can be seen that except for the polyurethane insulated wooden frame wall building, there isn't a big difference between the calculation results by using equation (5.2) and the measured ones. However, a more significant difference is observed between the measurement results and those calculated by using equation (5.3). The reason for this variation is not clear. Measurement errors could nevertheless be one possibility.

5.3 Infiltration/exfiltration energy losses

The annual infiltration/exfiltration energy loss results that were calculated by using equation (3.20) are shown in Table 5.3 while those obtained by using equation (4.8) are presented in Table 5.4. The results presented in Table 5.4 represent infiltration/exfiltration energy losses for seven months only and are categorised into two seasons in order to allow for comparisons with results presented into Table 5.3. Comparing the results in the two tables (5.3 and 5.4), it can be seen that for the winter season equation (3.20) gave results, which are approx. 23% greater than the results obtained through equation (4.8).

Table 5.3: Annual infiltration/exfiltration energy losses as per equation (3.20)

Building type	Infiltration/exfiltration energy losses, [kWh]			
	AUTUMN	WINTER	SPRING	TOTAL
Polyurethane insulated wooden frame wall	9.960	14.718	10.181	34.859
Insulated log wall	123.568	175.714	121.852	421.134
Autoclaved aerated concrete block wall	12.852	18.991	13.120	44.963

Likewise for the spring season, the results were greater by 15.8% to 19.2%. These differences may be linked to the differences in the wind speeds and temperature values that were used in the calculations. In the calculations with equation (3.20) wind speed and mean temperature values recorded over a period of 20 years (1961-1980) were used while for calculations with equation (4.8) on site measured data was used.

Table 5.4: Infiltration/exfiltration energy losses in 7 months as per equation (4.8)

Building type	Infiltration/exfiltration energy losses, [kWh]			
	AUTUMN	WINTER	SPRING	TOTAL
Polyurethane insulated wooden frame wall	-	11.208	8.568	-
Insulated log wall	-	136.145	99.035	-
Autoclaved aerated concrete block wall	-	14.677	10.601	-

Virtanen [1993] suggested that thermal coupling of leakage air and heat flows in buildings and building components be taken into account when calculating heating energy losses in buildings due to infiltration/exfiltration. He revealed that if the heat recovery effect of air leakage is considered, calculations of the total building heating load would give results which are 4 – 7.5% less if the annually averaged infiltration rate is 0.5 h^{-1} and 3 – 4% less if the average infiltration rate is 0.1 h^{-1}. His findings further indicated that if there are several leakage sites within the building envelope, then the heat recovery effect of leakage air on the total heating load is at its highest when the annually averaged infiltration rate is about 0.6 h^{-1}. On the other hand, if according to his report, there are fewer leakage sites, the heat recovery of leakage air on the total heating load is at highest when the average infiltration rate is about 0.3 h^{-1}.

It has also been reported that, the heat recovery effect of leakage air could also be taken into account in the calculation of heating load due to conduction heat losses with the help of an average modified Nusselt number for the building envelope. The modified Nusselt number is a factor by which the conventionally calculated heating load due to conduction heat losses is to be multiplied. Virtanen [1993] found that if, for example, the annually averaged infiltration rate of a building is 0.5 h^{-1}, the average modified Nusselt number, depending on the distribution of leakage sites and the air tightness of a building envelope, would be $Nu_{cd} = 0.89 - 0.94$. If the average infiltration rate is 0.1 h^{-1}, the Nusselt number would be, $Nu_{cd} = 0.95 - 0.97$, respectively.

The European Standard CEN [1997], highlighted that the heat recovery effect of infiltration air can be significant only when the ventilation air is circulated within parts of the building envelope (walls, windows, roofs), although the transmission heat loss is increased. Several conditions under which this phenomenon is applicable were also mentioned. The conditions are that:

- The air flow is parallel to the envelope surface
- The thickness of the air layer is between 15 and 100 mm
- The air tightness of the remaining parts of the envelope is high
- The requirements in Table C.1 (shown below) are met
- Supply air, if natural, is controlled through adjustable or self-controlled inlets located on the internal parts of the envelope.

Table C.1: Ventilation requirements for the application of heat recovery effect of infiltration air [CEN 1997]

Shielding class	**Requirement**
No shielding	Mechanical exhaust or supply
Moderate shielding	Mechanical exhaust or supply
Heavy shielding	No requirement

NOTE: *This method mainly applies where supply air is circulated within the building envelope elements. Exhaust air may also be used, provided that suitable provisions are made to avoid any troubles due to condensation.*

Findings by other researchers [Buchanan, 1998] regarding infiltration heat recovery suggest that about 10-20% of the heat would be recovered at 1 h^{-1} infiltration flow rates, so it's unlike that the infiltration heat recovery effect plays a large role in very leaky envelopes. In houses where infiltration rates can be quite low, infiltration heat recovery could have a significant effect, provided the infiltrating air goes through the insulating layers and not just directly through holes and cracks. However, this leakage scenario is associated with high flow exponents, which are not observed in most housing stock.

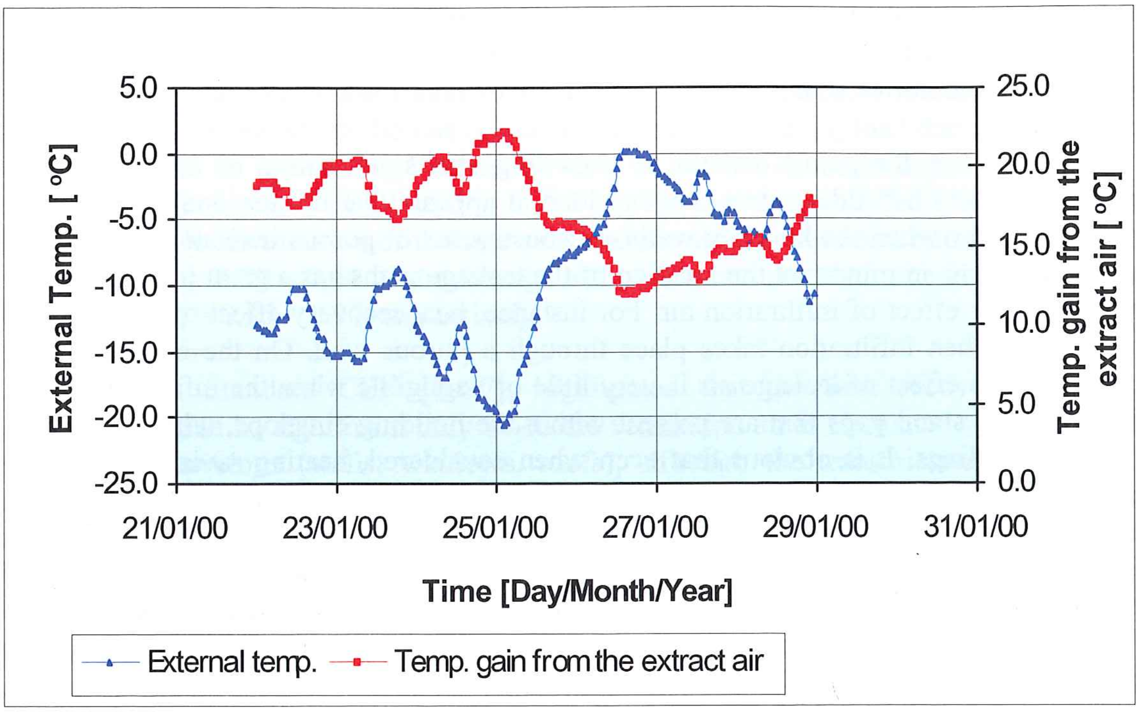
Consequently, this leakage scenario cannot be expected to occur, except in cases where it has been included in the design, as in dynamic insulation, and so, the infiltration heat recovery would not be large.

In view of the foregoing discussion regarding the significance of infiltration heat recovery effect on buildings total heating load, it appears that it's reasonable to consider this effect only when the building walls are constructed of porous insulation materials. It should be borne in mind that the location of the leakage paths has a great influence on the heat recovery effect of infiltration air. For instance, heat recovery effect of leakage air is significant when infiltration takes place through a porous wall. On the other hand, the heat recovery effect of leakage air is very little or negligible when the infiltration occurs through cracks and gaps that are present within the building envelope, which is the case in most buildings. It is obvious that even when considered, heating savings that can be achieved are far less compared to benefits that can be achieved when the building is completely airtight. In the present study, this phenomenon was not taken into account in the calculations of the total heating load of the buildings since most of the infiltration air entered the buildings though gaps and cracks. Based on the arguments given by other researchers regarding the issue, it can be assumed that even if considered, this factor would have had a very little effect on the obtained total heating load results.

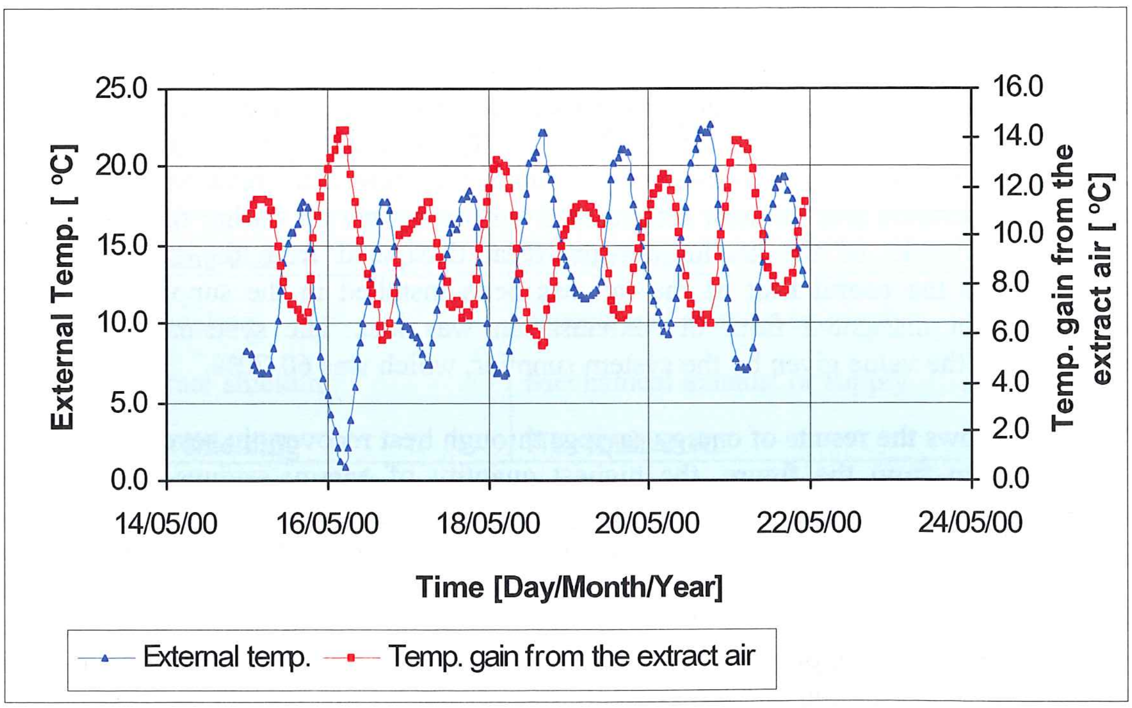
5.4 Annual energy savings through ventilation heat recovery

It was observed that the absolute quantity of energy savings through ventilation heat recovery increased as the outdoor temperature decreased. The calculated heat recovery efficiencies of the systems ranged from 42.5% to 70% during the warmest and the coldest week of the heating season respectively. Figure 5.1 shows the relation between the external temperature and the heat recovered from the extract air during the coldest and the warmest weeks of the heating season. Heat dissipated from the supply air fan contributed to the useful heat as the fan has been installed in the supply air stream. However, heat dissipated from the exhaust fan was lost. The systems' efficiencies conformed to the value given by the system supplier, which was 60-70%.

Figure 5.2 shows the results of energy savings through heat recovery in seven months. As it can be seen from the figure, the highest quantity of energy savings through heat recovery was achieved in the most airtight building, in this case the polyurethane insulated wooden frame wall building (test building number 1). It can also be seen that the difference among the recovered heat values within the three buildings is not significant. In principle, for buildings of equal volumes located in the same weather conditions with same indoor temperatures, supply and exhaust air change rates, their quantities of energy saving through heat recovery should be equal. In this particular study however, the observed difference among the obtained results was obviously caused by the variations in the indoor temperature values because of either infiltration or thermal inertia of the building structures. Research on the impact of ventilation upon energy consumption in buildings [Leal *et al*, 2000] indicated that the potential for heat recovery is higher in buildings with good insulation (low U-values).



(a) Coldest week of the season



(b) Warmest week of the season

Figures 5.1: Relation between the external temperature and the heat recovered from the extract air

The obtained energy savings results do not represent the annual energy savings through ventilation heat recovery, as the results for two months (September and October) were not included. Assuming that the quantity of energy saving through ventilation HR for the two months was 32 kWh (estimation based on the value obtained for November) the annual energy saving through ventilation HR for the polyurethane insulated wooden frame wall building would have been approximately 182 kWh. If a normal residential building of say 300-m^3 volume is considered, it can be seen that the annual heating energy savings through ventilation HR would be 3640 kWh, which is approximately 12 kWh/m^3. Also, if comparison is made between the most airtight and the most leaky (less tight) buildings in terms of heating energy savings through ventilation HR, it is evident that the energy savings through HR would be approx. 20% higher in the tighter building. Jokinen [1998] found that in buildings ventilated by mechanical ventilation systems without heat recovery, the average energy consumption due to mechanical air change was 11494 kWh/a with an average of 14.7 kWh/m^3 annually for each individual building. In buildings ventilated by mechanical ventilation systems with heat recovery, the proportion of energy loss due to air change was found to decrease by 20%. In this study, it was found that the quantity of ventilation energy recovered from the polyurethane insulated wooden frame wall building is about 34% of the total ventilation energy consumption.

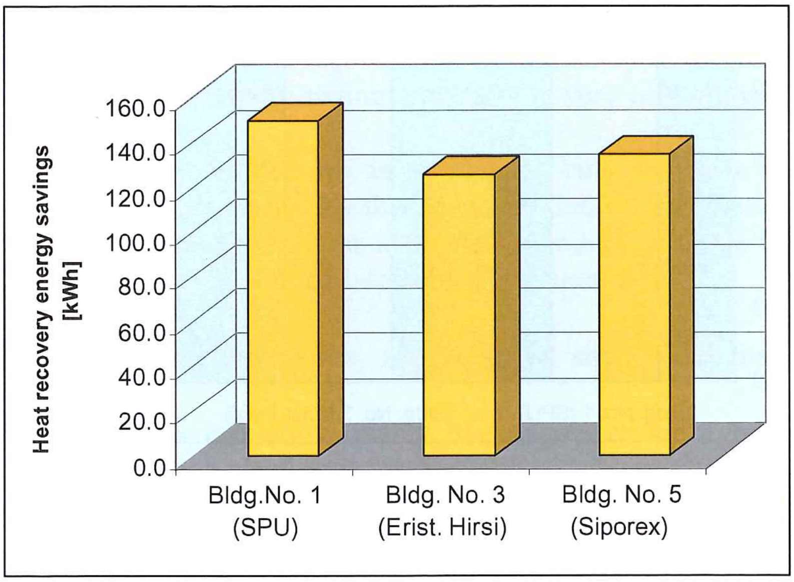


Figure 5.2: Energy savings through ventilation HR in seven months

It was found that, in buildings ventilated by mechanical ventilation systems without heat recovery the proportion of energy loss due to air change was 47% of the buildings' heating energy consumption [Jokinen, 1998]. Investigations also revealed that the highest heating energy consumption occurred in buildings where airing was often carried out by opening windows and also in buildings without ventilation heat recovery.

5.5 Annual total ventilation energy consumption

The impact of the air tightness of the building envelope on efficiency of ventilation systems with heat recovery was clearly reflected on the annual total ventilation energy consumption in each of the three test buildings. The results are shown in Figure 5.3. The results have strongly confirmed that the leakier the building envelope, the greater the overall quantity of ventilation energy consumption in a building. The quantity of ventilation energy consumption in the insulated log wall building, which had the least degree of air tightness, was 37.1% and 35.3% higher compared to that of polyurethane insulated wooden frame wall and autoclaved aerated concrete block wall buildings respectively.

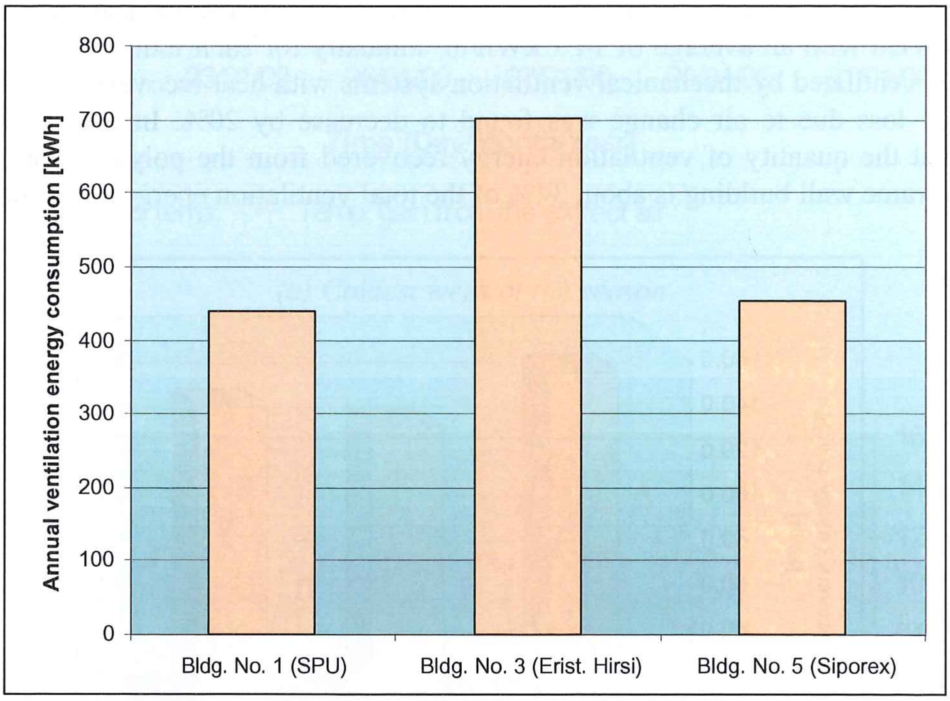


Figure 5.3: Total ventilation energy consumption for the three test-buildings in seven months

6. IMPLICATION OF THE DEGREE OF ENVELOPE AIR TIGHTNESS TO THE OVERALL HEATING ENERGY CONSUMPTION IN A NORMAL RESIDENTIAL BUILDING

The main purpose of constructing airtight buildings is to keep warm air inside during winter and cool air inside during summer. The less energy needed for heating or cooling, the lower the building energy consumption. Most building heat loss occurs through conduction and air change (mechanically and/or infiltration/exfiltration). Thermal conductivity of deferent building materials differs; with some having low and some having higher values. Conduction heat losses depend on the thermal conductivity of materials used to construct the building and on the temperature difference across the walls, roof, windows, and doors. The greater the temperature difference, the greater the heat loss. Heat losses through air leakage takes place by convection, or the transfer of heat by the motion of the heat-carrying fluid (a gas or liquid). Also the movement of hot air up a chimney causes a convection heat loss.

Measures to improve the energy efficiency of a building involve decreasing heat losses by conduction and infiltration/exfiltration including installing energy efficiency appliances and using solar energy for space and water heating. About one-third of the heat loss in a typical single-family home is through exfiltration of warm inside air to the cold outside [Turiel 1985, Meyer 1983]. Using ventilation systems with heat recovery also can result in a significant energy saving especially in very cold climates.

On general terms, energy consumption in residential buildings can be divided into passive consumption, which is caused by the structures due to workmanship mistakes in outer walls and active consumption that is related to building usage and occupancy. These two groups can further be divided into subgroups such as:

- Location of the building, orientation, size, climate, shape, and the energy design strategy of the building
- The building envelope's insulation quality, the degree of air tightness, ventilation strategy, and the ventilation air change rates
- Lightning and quantity of domestic and sanitary hot wastewater
- The number and age of buildings' occupants
- The building consumer (occupants) social and cultural habits

A number of research studies on various aspects regarding buildings' heating energy consumption has been carried out at Tampere University of Technology in the laboratory of Structural Engineering. These researches focused mainly on the following:

- Conduction heat losses
- Air change energy losses
- Ventilation heat recovery
- Heat losses due to uncontrolled air leakage (infiltration/exfiltration)
- Higher indoor temperature set-points due to draughts in leaky buildings

Results obtained from the previous studies were applied in the current study with the purpose of analysing the overall heating energy consumption in the so-called 'Example Building'.

6.1 Specifications of the 'Example Building'

In the analysis of overall heating energy consumption in buildings, an example building with the following specifications was used:

Overall dimensions (roughly):	10 x 10 x 2.5 m^3
Total area	100 m^2
Windows' area	15 m^2
Doors' area	5 m^2
Floor area	100 m^2
Ceiling area	100 m^2
Walls area (40 x 3) - 20	100 m^2
Total volume	300 m^3

The example building is assumed to be equipped with a balanced mechanical ventilation system with heat recovery. The average heat conduction coefficients this building in accordance with the current heat insulation regulations is shown in Table 6.1 below.

Table 6.1: The average heat conduction coefficients in accordance with the current Finnish regulations

Building component	Area, **A** [m^2]	Coeff. of thermal transmittance, **U**, [$Wm^{-2}K^{-1}$]	**A x U** [WK^{-1}]
Floor	100	0.22	22.0
Ceiling	100	0.22	22.0
Walls	100	0.28	28.0
Windows	15	2.1	31.5
Doors	5	0.7	3.5
	320		**107.0**

U_{aver} = 107/320 0.33 Wm-2K-1

Assume that the heating season last for 9 months, which is approximately 270 days and the average outdoor temperature is +2 °C. Furthermore, assume a constant indoor temperature of +20 °C. With these assumptions in mind, the heating degree-days for the whole heating season $\boldsymbol{D_d}$, will be:

$$D_d = 270 \times 18 = 4860\ ^{\circ}\mathrm{C.d}$$

6.2 Heating energy losses due to conduction

Transmission heat losses depend on the heat conduction through the building envelope. In a simplified form, it can be determined by multiplying the building area with the coefficient of thermal transmittance (U-value) and the indoor-outdoor temperature difference. Thus the heating energy losses due to conduction, Q_{cond}, is given by:

$$Q_{cond} = [(U \text{ x } A) \text{ x } D_d \text{ x } 24]/1000$$

$$= (107 \text{ x } 4860 \text{ x } 24)/1000 = 12480.48 \text{ kWh} \quad 12.5 \quad \text{MWh}$$

In a research by [Lindberg *et al* 1998] it was found that the current values for conduction heating energy losses through walls of small buildings (i.e. single family dwellings) are over-estimated by about 50%. The following reasons could offer some explanation on what causes such a huge overestimation:

1. The U-values used are normally estimated values (i.e. averaged values are used in the calculations of conduction heat losses).
2. The conduction heat losses are calculated by using the outer surface area of buildings instead of taking the central axis area. This over-estimation significantly influence the conduction heat loss results
3. Thermal inertia of the walls due to solar radiation

The real buildings' conduction heat losses are somewhat 20-30% less than the calculated ones [Lindberg *et al* 1998]. Therefore, for the considered example building, the real heating energy need would be somewhere around:

$$Q_{cond} \quad 0.75 \text{ x } 12.5 \quad 9.4 \quad \text{MWh}$$

6.3 Mechanical air change energy consumption

The mechanical ventilation energy losses depend on the ventilation strategy, ventilation rate, and the indoor-outdoor temperature difference. Let's assume that during the whole heating period the air change rate is kept constant at 0.5 h^{-1}. The energy needed to rise the temperature (to heat) of 1 m^3 of air by 1 °C is given by:

$$Q = 1.2 \text{ kg x } 1.0 \text{ kJ/kg/°C x } 1\text{°C} = 1.2 \text{ kJ} \quad 3.3 \text{ x } 10^{-4} \text{ kWh}$$

In every one hour, the quantity of air that is changed (removed from the building) is equal to 0.5 x 300 = 150 m^3/h. The energy needed to heat the replacing fresh air is therefore:

$$Q_{ach} = 150 \text{ x } 4860 \text{ x } 24 \text{ x } 3.3 \text{ x } 10^{-4} \quad 5800 \text{ kWh} \quad 5.8 \quad \text{MWh}$$

6.4 Infiltration/exfiltration energy losses

Numerous studies have confirmed that the uncontrolled air change in buildings is mostly dependent on the air tightness of building envelopes. The air tightness of a building envelope is normally determined through pressurisation/depressurisation tests at 50 Pa pressure difference. (The number of air changes per hour at $p = 50$ pa). Based on a number of research results that were obtained through experimental studies, the average quantity of uncontrolled air change in buildings is about $n_{50}/20$. This means that, in a complete air tight building where (i.e. $n_{50} = 0$), there won't be any uncontrolled air change or, in other words, no air leakage. In normal conditions, for a building with $n_{50} = 7$, the uncontrolled air change will reach somewhere around 0.35 h^{-1}, same as what standards and regulations demand as a minimum air change rate in a residential building. In a worst case, when $n_{50} = 15$, the uncontrolled air change rate will reach 0.75 h^{-1}, which is almost twice as much as the minimum required air change rate.

Naturally, wind and indoor-outdoor temperature difference (buoyancy) cause the uncontrolled air changes in buildings. For this reason the uncontrolled air change rate largely depend on buildings' characteristics. During calm days (without wind), there is almost no uncontrolled air change whereas in very windy days the number of uncontrolled air change increases dramatically.

Energy due to air change is remarkably influenced by the mechanical ventilation air change, whereas in leaky buildings the uncontrolled air change adds further to the quantity of air change, which reduces the heat recovery efficiency of ventilation systems.

The uncontrolled air change rates (infiltration/exfiltration) were predicted by making use of pressurisation tests results at $p = 50$ pa. This was performed by calculating the quantity of air leakage at different pressure differences that are caused by wind. The wind speed data has been researched and documented for many years, in which the annual air change due to wind can be estimated based on the available data. Applying this method to the test buildings at TUT, the obtained uncontrolled air changes were very close to the values for the uncontrolled air change rate obtained by using the measured data.

For the example building, the applied quantity of uncontrolled air was taken roughly as,

$$300 \text{ x } n_{50}/20 \text{ or } 15 \text{ x } n_{50}, \text{ m}^3$$

Energy loss due to uncontrolled air change (infiltration/exfiltration) for the example building can be calculated as follows:

$$Q_{inf} = 15 \text{ x } n_{50} \text{ x } 4860 \text{ x } 24 \text{ x } 3{,}3 \text{ x } 10^{-4} \quad 0.6 \text{ x } n_{50} \text{ MWh}$$

6.5 Ventilation heat recovery

The ventilation heat recovery device recovers heat from the extract air that passes through the system for preheating the incoming cold supply air. In addition the device needs energy for its operation but in a small quantity, which was not taken into consideration in the present study. Taking the heat recovery efficiency of the ventilation system to be 60%, the quantity of the recovered heat energy would be approximately:

Q_{hr} -0.6 x 5.8 -3.5 MWh

6.6 Influence of envelope air tightness on the indoor climate

Leakage air can give rise to cold air draughts inside buildings, which must be compensated for by an increase in room temperature, which in turn causes increased energy losses. For example, during winter at –10 °C temperature with a 10 m/s wind, people feels as cold as if the temperature was – 22 °C in calm weather [RT 05- 10390]. Generally, it can be said that in cold winds people tend to keep indoor temperatures at sufficiently high levels due to cold air draughts. This explains the reasons why indoor temperature set points are kept high in buildings that are not sufficiently air tight in windy and moderate windy conditions.

Considering the example building, we assume that, for every one-third increase in the number of air changes at n_{50} the indoor temperature increases linearly by 1 °C. Since the indoor-outdoor temperature difference during the heating season was assumed to be 18 °C, an increase of 1 °C in the indoor temperature will lead to an increase in the heating energy need by 1/18. With the above assumptions in mind, a correction factor, K, for the heating energy demand in leaky buildings can be calculated as follows:

$$K = 1 + \frac{n_{50}}{3} \times \frac{1}{18} \approx 1 + 0.02 \times n_{50}$$

This correction factor will affect, in an increasing order, all the formerly calculated heating energy demand, Q_{cond}, Q_{ach}, and Q_{inf}. It will also cause an increase in the quantity of energy recovered, Q_{hr}.

6.7 Influence of other factors not considered in the study

Part of the buildings' heating energy is lost through hot wastewater. Energy losses through sewage wastewater depend on the quantity of water used in the building and the temperature difference of the water entering and leaving the building. Also buildings gain some incidental energy from solar radiation, occupants, lighting, hot water, and domestic appliances. The calculation method discussed in this example is limited to calculations of energy losses by transmission and ventilation, thus neglecting the hot wastewater losses.

In addition, the calculation method did not take into account the free heat gains of the building as it could have made the calculations even more complicated to deal with.

The approach taken in this study concerns the whole building energy consumption taking into consideration the influence of buildings' air tightness on heating energy need estimations. The examination was carried out through calculations with several assumptions and thus the values obtained are only average values. Some of the values used in the calculations however, are considered to be the exact/real values as they were obtained through previous empirical studies.

In Finland heating energy consumption in buildings is estimated based on the Finnish Building Code of Practice Part D5. Other countries such as Germany often use similar typical Codes of Practice in their calculations for buildings' heating energy consumption. Most of the values given in these codes however, are often based on theoretical calculations. Figures 6.1-6.3 shows the total heating energy consumption in a building as a function of the building air tightness at various envelopes average U-values. In these Figures the difference between the energy results calculated as per Finnish Building Code of Practice (D5) and the method used for the example building is clearly illustrated. Figure 6.4 combines the former three Figures (6.1-6.3) together in order to portray the influences of the building envelope average U-value on the total heat energy consumption in buildings. Figures 6.5-6.7 presents the conduction, air change, and infiltration energy losses for the example building when different cases for ventilation strategy, degree of envelope air tightness, and U-values are considered.

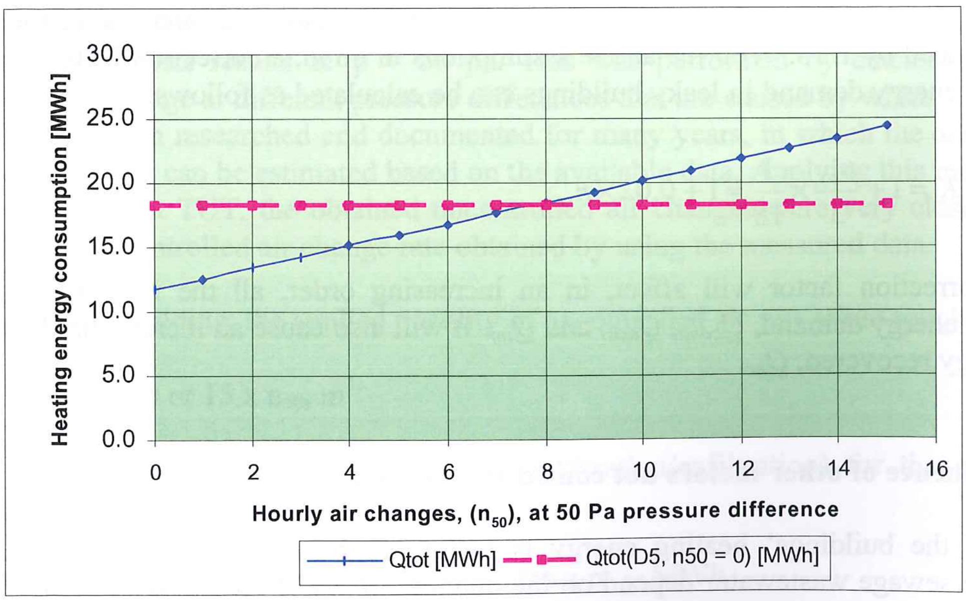


Figure 6.1: Heating energy consumption – Example building, U-value = 0.33 W.m^{-2}.K^{-1}

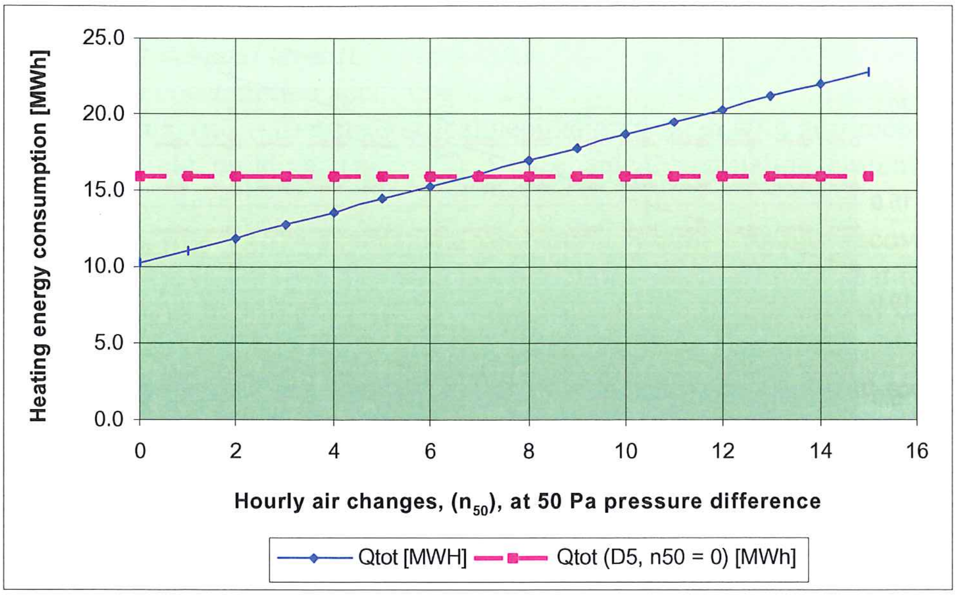


Figure 6.2: Heating energy consumption – Example building, U-value = 0.28 $W.m^{-2}.K^{-1}$

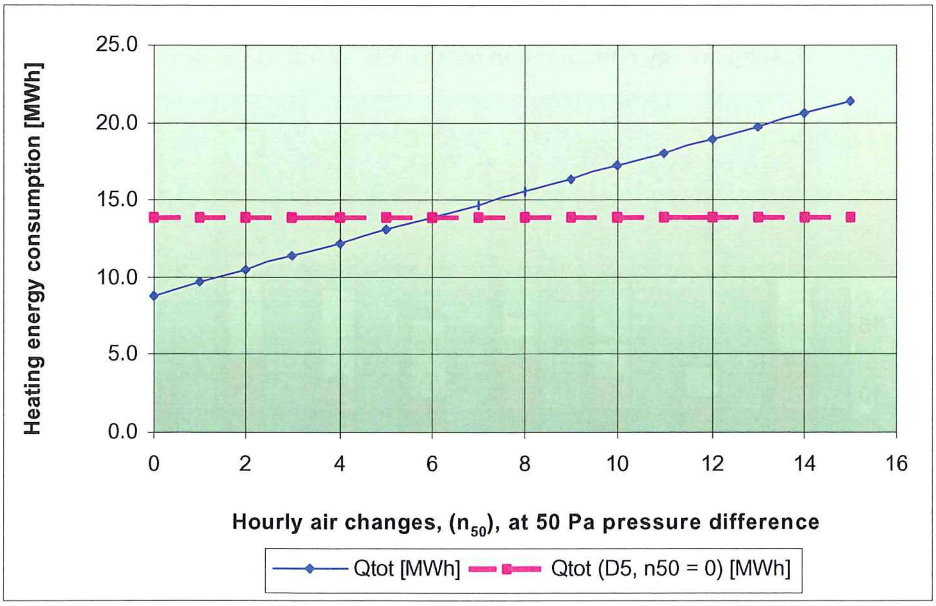


Figure 6.3: Heating energy consumption – Example building, U-value = 0.23 $W.m^{-2}.K^{-1}$

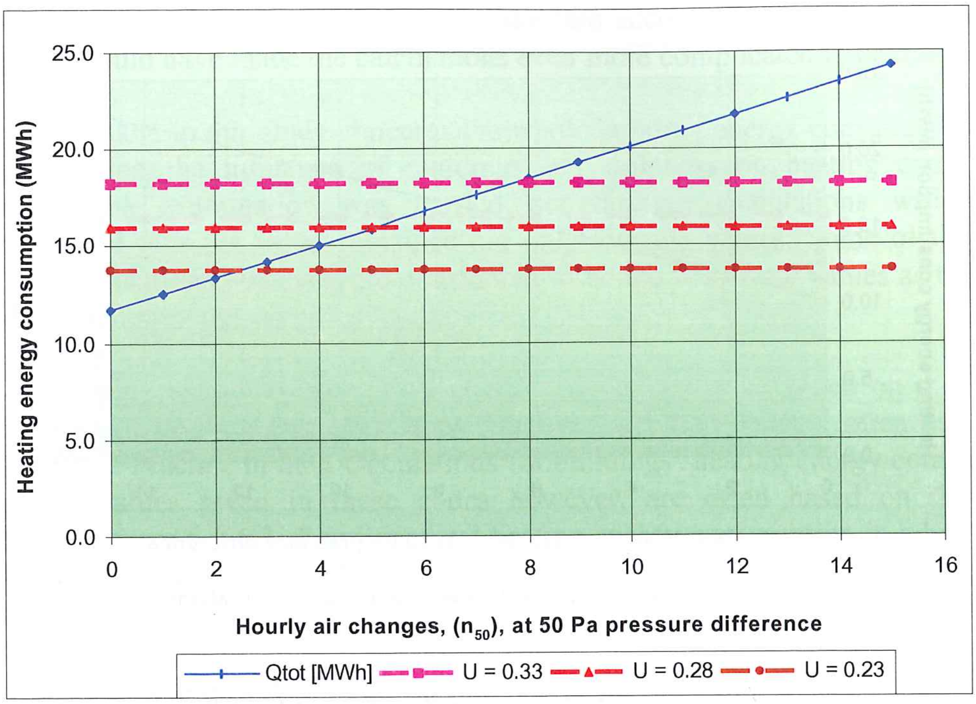


Figure 6.4: Impact of envelope air tightness on heating energy consumption: Comparison between the current code of practice and the Finnish CP-D5

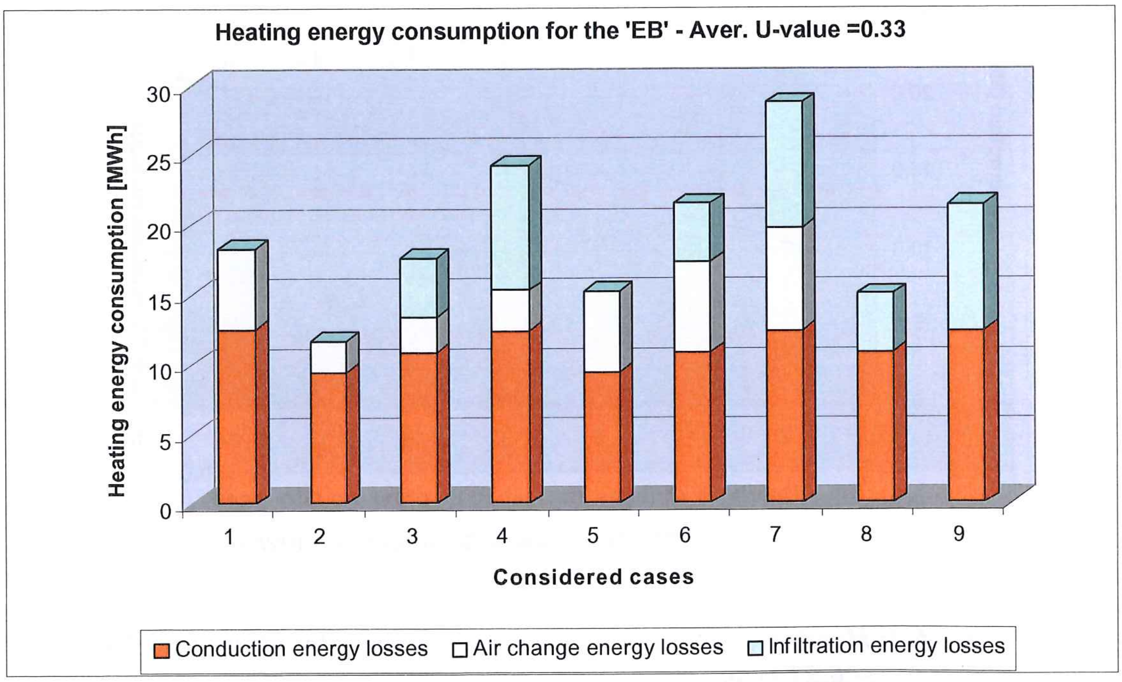


Figure 6.5: Heating energy consumption for the Example Building when different cases are considered with average U-value = $0.33W/m^2.K$

Definition of the cases considered in Figure 6.5:

Cases 1-9: Current demand level ($U = 0.33\ W/m^2.K$)

1. Heating energy consumption according to the Finnish Building Code (D5) demands
2. Air tight building, ($n_{50} = 0$) + mechanical ventilation system with heat recovery
3. Moderate air tight building, ($n_{50} = 7$) + mechanical ventilation system with heat recovery
4. Leaky building, ($n_{50} = 15$) + mechanical ventilation system with heat recovery
5. Air tight building, ($n_{50} = 0$) + mechanical ventilation system without heat recovery
6. Moderate air tight building, ($n_{50} = 7$) + mechanical ventilation system without heat recovery
7. Leaky building, ($n_{50} = 15$) + mechanical ventilation system without heat recovery
8. Moderate air tight building, ($n_{50} = 7$) naturally ventilated
9. Leaky building, ($n_{50} = 15$) naturally ventilated

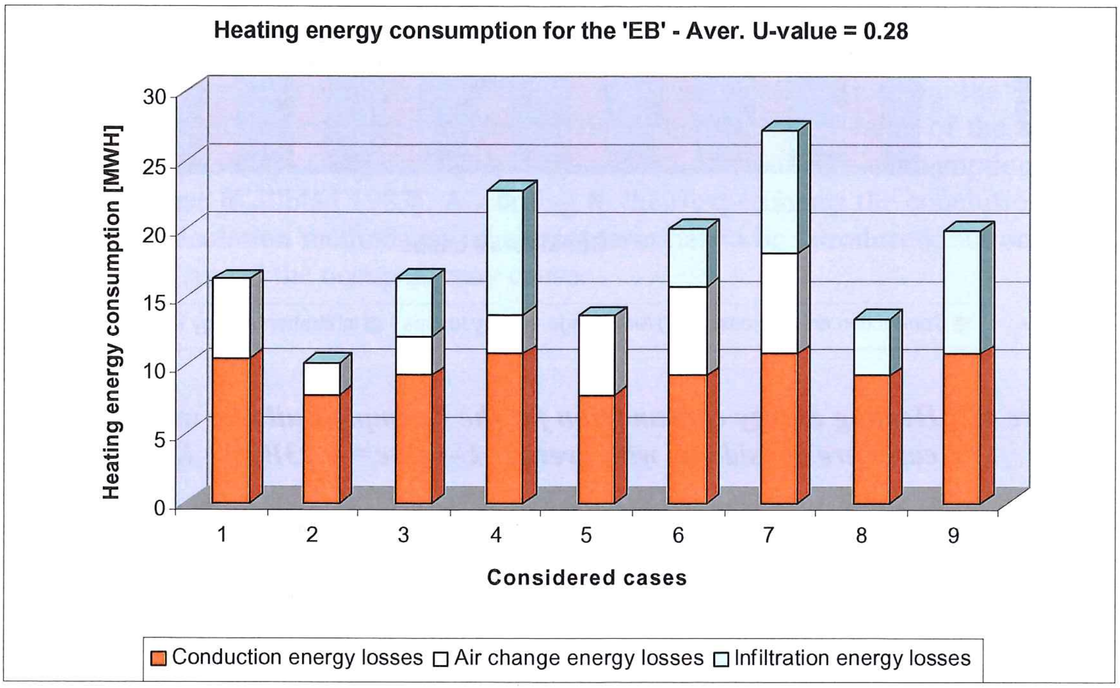


Figure 6.6: Heating energy consumption for the Example Building when different cases are considered with average U-value = $0.28 W/m^2. K$

Cases 1 –9: Current demand level with 15% reduction in U-value ($U = 0.28$)

1. Heating energy consumption according to the Finnish Building Code (D5) demands
2. Air tight building, ($n_{50} = 0$) + mechanical ventilation system with heat recovery
3. Moderate air tight building, ($n_{50} = 7$) + mechanical ventilation system with heat recovery
4. Leaky building, ($n_{50} = 15$) + mechanical ventilation system with heat recovery

5. Air tight building, ($n_{50} = 0$) + mechanical ventilation system without heat recovery
6. Moderate air tight building, ($n_{50} = 7$) + mechanical ventilation system without heat recovery
7. Leaky building, ($n_{50} = 15$) + mechanical ventilation system without heat recovery
8. Moderate air tight building, ($n_{50} = 7$) naturally ventilated
9. Leaky building, ($n_{50} = 15$) naturally ventilated

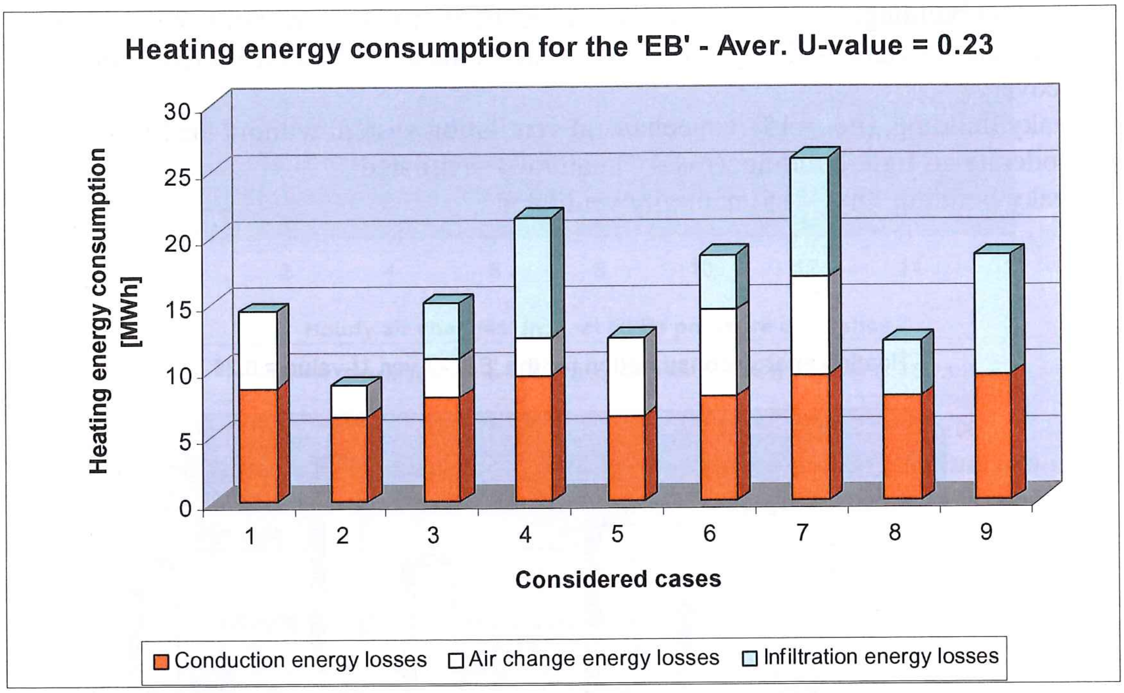


Figure 6.7: Heating energy consumption for the Example Building when different cases are considered with average U-value = 0.23W/m². K

Cases 1 –9: Current demand level with 30% reduction in U-value (U = 0.23)

1. Heating energy consumption according to the Finnish Building Code (D5) demands
2. Air tight building, ($n_{50} = 0$) + mechanical ventilation system with heat recovery
3. Moderate air tight building, ($n_{50} = 7$) + mechanical ventilation system with heat recovery
4. Leaky building, ($n_{50} = 15$) + mechanical ventilation system with heat recovery
5. Air tight building ($n_{50} = 0$) + mechanical ventilation system without heat recovery
6. Moderate air tight building, ($n_{50} = 7$) + mechanical ventilation system without heat recovery
7. Leaky building, ($n_{50} = 15$) + mechanical ventilation system without heat recovery
8. Moderate air tight building, ($n_{50} = 7$), naturally ventilated
9. Leaky building, ($n_{50} = 15$), naturally ventilated

From Figures 6.5-6.7 it is clear that reducing the infiltration/exfiltration air in buildings through construction of airtight buildings could have the same effect as reducing the average U-value of buildings. This is an indication that if both insulation levels and air tightness of buildings are improved, significant heating energy savings in buildings can be achieved. It can also be inferred from the same Figures that buildings with different characteristics could have the same quantity of heating energy consumption.

The number and behaviour of building occupants normally influence the energy consumption of residential buildings. Thus, the occupants and their behaviour must be taken into account when analysing the building heating energy consumption. Even for identical houses, large variations in energy consumption can be observed, that are characterised by the occupants' behaviours. The influence of the occupants may also have a specific national character such as the use of buildings related to traditions and cultures of the area in question (i.e. saunas in Finnish dwellings). Also social factors such as family size, etc. might influence heating energy consumption in buildings.

Sometimes the behaviour of the occupants may be related to indoor climate. For example, a high indoor temperature can result in the opening of windows and turning down the thermostat or airing by opening windows when ventilation systems do not function efficiently. The outdoor climate may also influence the occupants' behaviour. For example, the use of lighting and blinds which depend on the amount of daylight and the solar radiation reaching into the building. A Swiss investigation on the occupant influence on heating energy consumption revealed that the mean value of the occupant influence is practically zero, but with a spread of 50% of the consumption of the unoccupied house [Källblad 1983]. According to their experiments the conclusion is that in simplified calculation methods no inhabitant term has to be introduced, but one has to be aware of the spread the occupant may cause.

7 CONCLUSIONS AND RECOMMANDATIONS

7.1 Conclusions

This study presents findings regarding the impact of the air tightness of the building envelope on the efficiency of balanced mechanical supply and extract ventilation systems with heat recovery (MVHR) in residential buildings. The study contributes to the understanding of the technical viability of implementing MVHR systems in residential buildings. The relationship among important factors consisting of the degree of envelope air tightness, the heat recovery performance, climatic weather and the total heating energy consumption in buildings was investigated.

The results obtained in the study have strongly confirmed that the degree of building envelope air tightness is a key factor to the overall performance of buildings as regards to energy, Indoor Air Quality and comfort. The interaction of the degree of envelope air tightness with other building components including ventilation systems and the climatic control systems were found to be of equal importance. While the focus was on the impact of envelope air tightness on energy efficiency of the buildings, high quality should also be aimed at when it comes to aspects like structural durability, heat insulation, indoor air quality, comfort, moulds, moisture, acoustic etc.

A theory applicable to theoretical prediction of air change rates in buildings due to various pressure differences and wind speeds (natural conditions) based on the degree of air tightness of the building envelope was developed and tested. The calculation results obtained through the developed theory were found to agree very well with the calculation results that were obtained by using another equation that was obtained from the existing literature.

The results revealed that a significant quantity of heating energy in buildings is lost due to uncontrolled air changes. For example, it was found that the annual quantity of heating energy loss due to infiltration/exfiltration in the insulated log wall building (Hirsi seinä) which had 11.1 h^{-1} (ach) degree of air tightness, is approx. 28.076 kWh/m^3 annually. On the other hand, the annual quantity of heating energy loss due to infiltration/exfiltration in the polyurethane insulated wooden frame wall building (SPU) and the autoclaved aerated concrete block wall building (Siporex) was 2.324 kWh/m^3 and 3 kWh/m^3 respectively. This indicates that infiltration energy loss in the insulated log wall building (Hirsi seinä) is 91.7% and 89.3% more compared to that of SPU and Siporex buildings respectively.

The results also showed that the energy savings through implementation of mechanical ventilation systems with heat recovery systems (MVHR) is significant enough to merit the adaptation of these systems in all Finnish residential buildings. In this case, it should however be emphasised that careful attention must be paid to the degree of envelope air tightness. It is suggested that for buildings that are ventilated by MVHR their degree of envelope air tightness should strictly not exceed 1.5 h^{-1} (ach) at 50 Pa pressure difference if potential energy savings through heat recovery (HR) are to be expected. For instance, the annual energy savings through ventilation HR in the polyurethane insulated wooden frame wall building (Siporex), which was the most airtight was about 12.133 kWh/m^3 in seven months of the heating season. This is a very significant quantity of energy savings especially if considered in terms of the 630 billions m^3 [Nippala *et al*, 1995] volume of detached, semi-detached, and apartments housing in Finland. In other words, if such energy quantity is to be recovered from all detached, semi-detached, and apartments in Finland, there would be energy saving of more than 2123.275. 10^6 GJ annually in Finland.

It was also found that the absolute quantity of energy savings through ventilation heat recovery increased as the outdoor temperature decreased. The heat recovery (HR) efficiencies of the ventilation systems tested were found to vary within the range between 42.5% and 70% depending on the outdoor temperature.

The impact of the degree of air tightness of the building envelope on efficiency of ventilation systems with heat recovery was clearly reflected in the annual total ventilation energy consumption of the three test buildings. Evidence clearly confirmed that the leakier the building envelope, the greater the overall quantity of ventilation energy consumption in a building. The total ventilation energy consumption in the insulated log wall building, which had the least degree of air tightness (i.e. 11.1 h^{-1}), was 37.1% and 35.3% higher compared to that of polyurethane insulated wooden frame wall and autoclaved aerated concrete block wall buildings respectively.

The research findings suggest that there is a need for improvements in the quality of building envelopes and, in particular, the degree of air tightness and insulation levels. These findings are of crucial importance to the building industry, building consumers (occupants) and the mechanical ventilation systems producers as the use of energy and its environmental impact such as global warming is currently a central issue of concern that scientists throughout the world are trying to solve.

The degree of envelope air tightness should be set at approximately one air change per hour (1 h^{-1}) based upon the Swedish experience [Elmroth at el. 1983] if the mechanically ventilated residential building is to achieve the goal of providing the desired ventilation rates free from undesirable weather influences due to air infiltration. Larger buildings require even tighter construction standards. In houses designed to use mechanical air exhaust ventilation systems, it must be ensured that the in-coming supply air does not create drafts that may cause discomfort for the occupants.

In houses ventilated by MVHR systems, care must be taken to avoid positive pressure inside the buildings as this could force the moisture-laden interior air into the walls, ceilings, and floors causing condensation problems and hence structural moisture damage. In order to reduce the risk of structural moisture damage, vapour barriers should applied to all exterior walls.

7.2 Recommendations for future research

The findings of this study delineated areas for further research, which could lead to increased optimisation of the heating energy consumption in buildings and the overall performance of ventilation systems. The main uncertainty in estimating the quantity of heating energy loss in buildings due to air leakage is linked to the determination of the quantity of uncontrolled air changes in buildings. The existing methods for determining the later were found to be too difficult to use or require too much input data that is not always available. It is therefore recommended to carry out more experimental tests to determine the quantity of air leakage in the test buildings in order to verify the developed theory, which could be easily applied in practice.

Experiences acquired from the study indicated that occasionally ventilation heat recovery might lead to over heating (too high temperatures) in buildings, even during the heating season at certain outdoor temperatures. This phenomenon was observed in the test buildings and is undesirable as far as comfort in buildings is concerned. This is also another area, which needs further research that could bring home necessary knowledge for MVHR improvements. It is proposed to carry out statistical analysis to determine the boundary line for the maximum outdoor temperature beyond which no further energy savings can be made. The knowledge could be used by the MVHR producers to modify their products by adding temperature sensors and supply air bypass ducts into MVHR systems.

The maximum HR set-point temperature would be the one that will be defined statistically and coupled with the bypass supply air ducts, they could eradicate overheating problems in buildings. The modified ventilation systems could work as follows: the temperature sensors will be installed in the supply air duct that takes the supply air to the heat recovery device. Once the temperature sensor senses that the supply air (outdoor air) temperature has reached the maximum HR set-point temperature, the air inlet to the HR device will automatically be triggered to shut off. At the same time, the bypass supply air inlet will automatically open to allow the supply air to be supplied directly into the building without being preheated.

Houses with tighter-fitting doors and windows should be constructed in order to combat infiltration/exfiltration through doors and windows. Leaks in the building envelope should be sealed with caulking compound. It is also recommended to carry out further research on the influence of the building occupants' behaviour on buildings' overall heating energy consumption.

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APPENDICES

Appendix 1: Plan of the test buildings.

Appendix 2: Cross-section – Polyurethane insulated wooden frame wall building.

Appendix 3: Cross-section –Insulated log wall building.

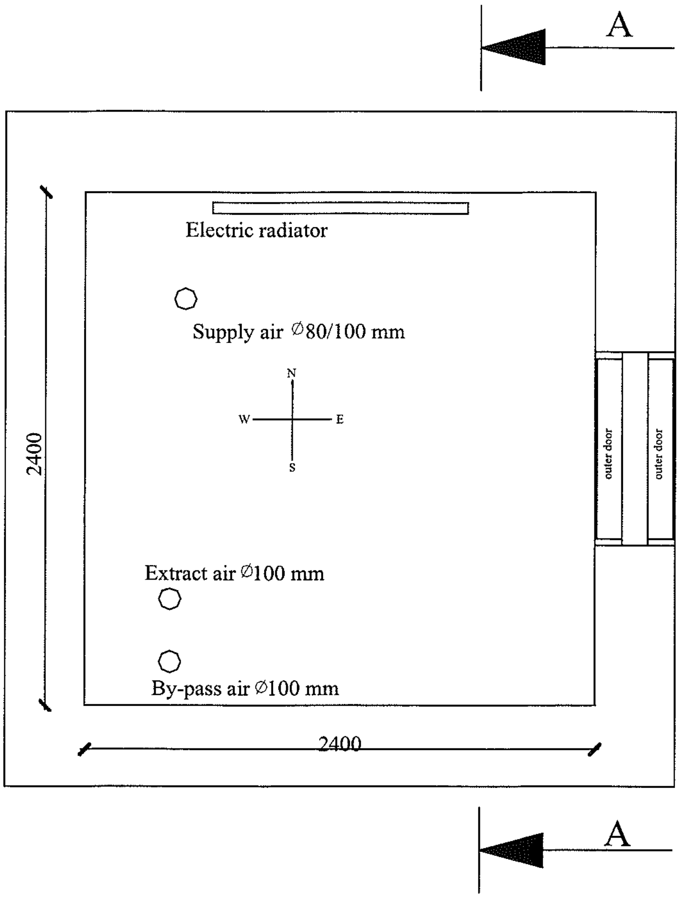
Appendix 4: Cross-section –Autoclaved aerated concrete block wall building.

Appendix 5: Details of the external walls.

Appendix 6: Ventilation system's technical specification.

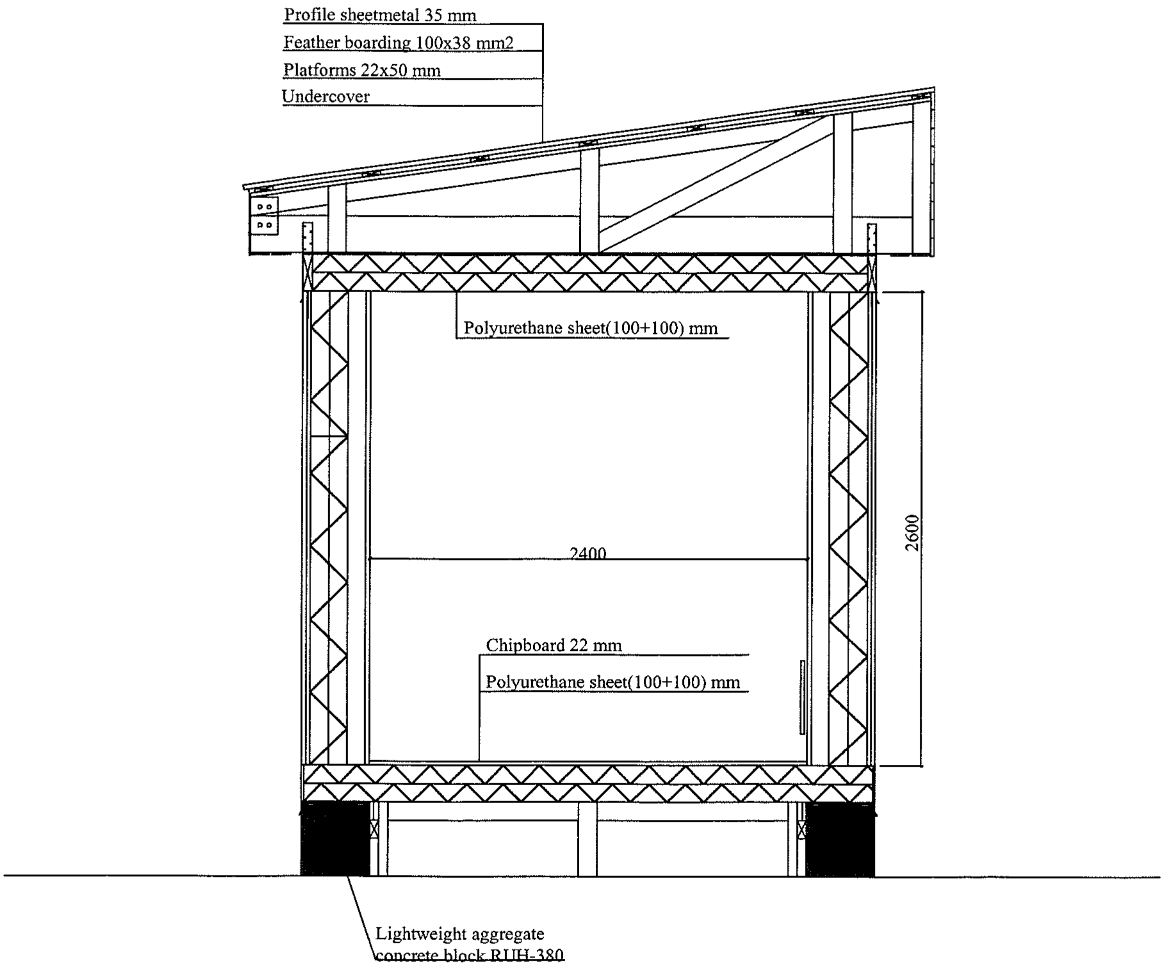
APPENDIX 1

Plan of the test buildings



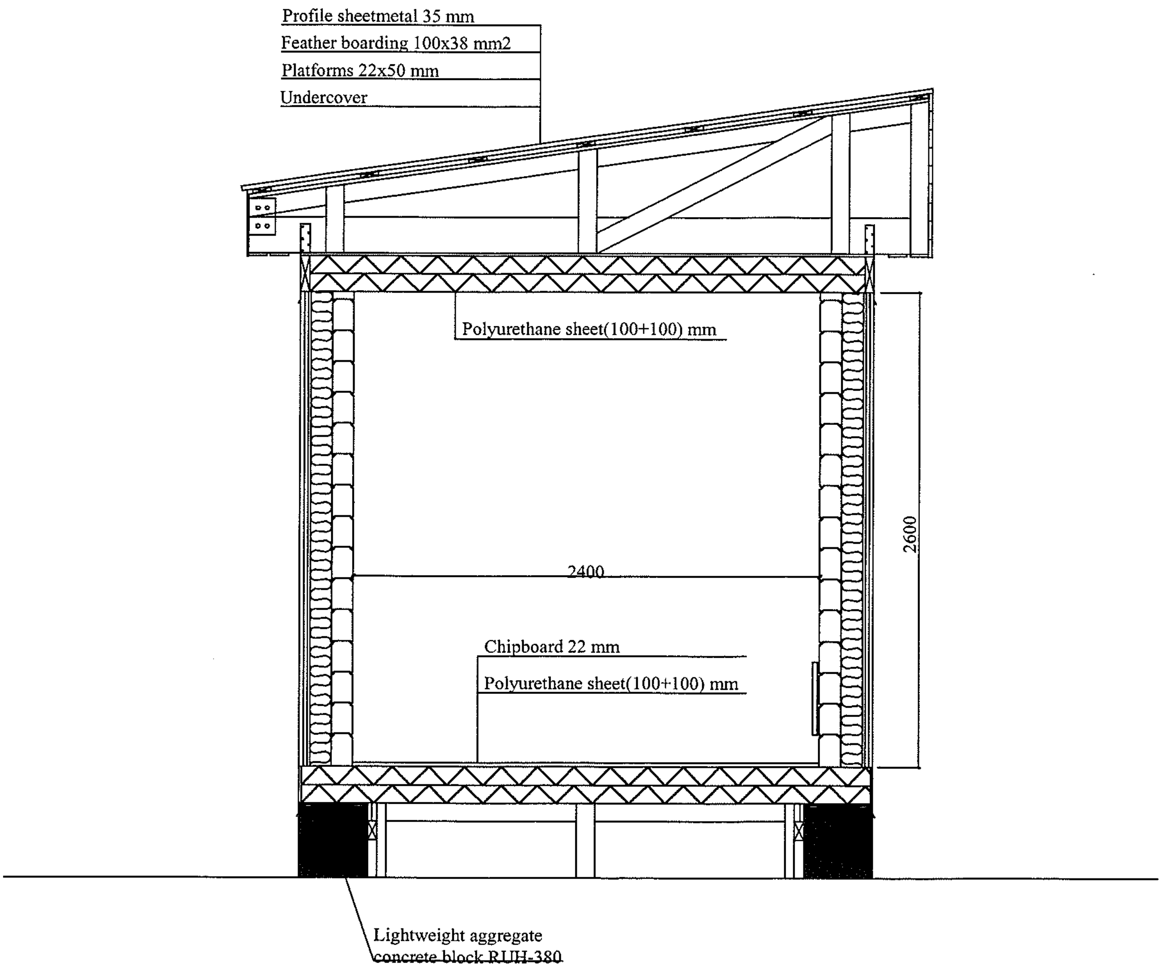
APPENDIX 2

A cross-section of the polyurethane insulated wooden frame wall building



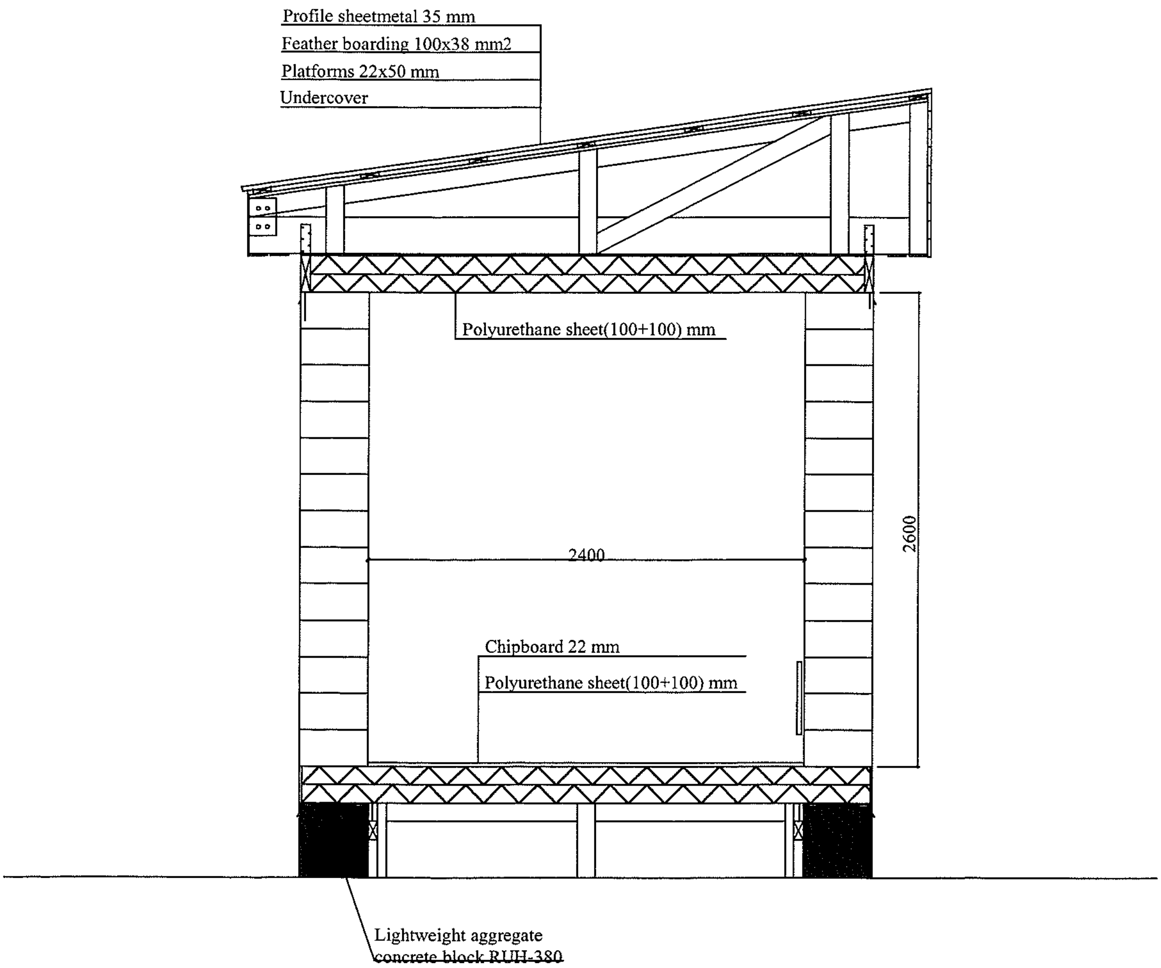
APPENDIX 3

A cross-section of the insulated log wall building



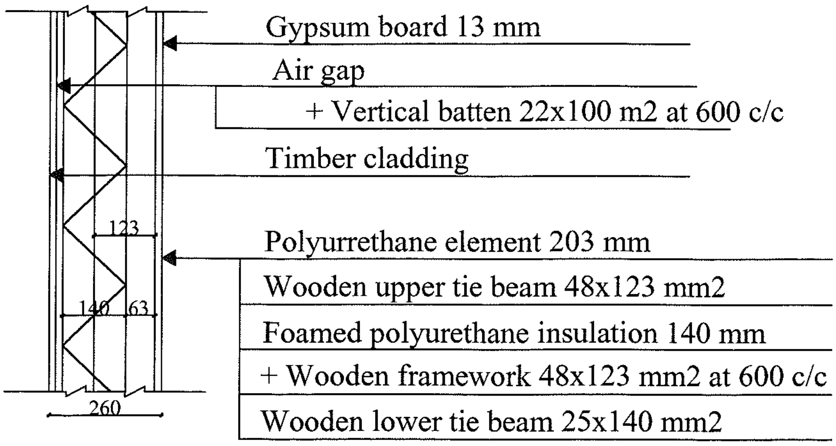
APPENDIX 4

A cross-section of the autoclaved aerated concrete block wall building

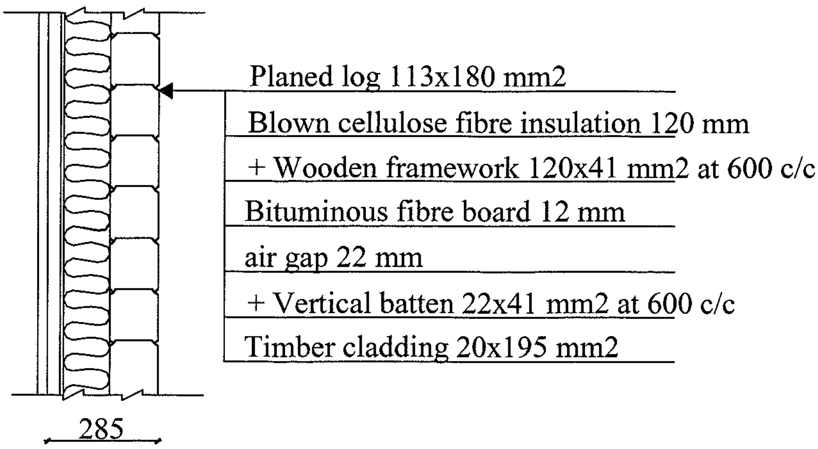


APPENDIX 5

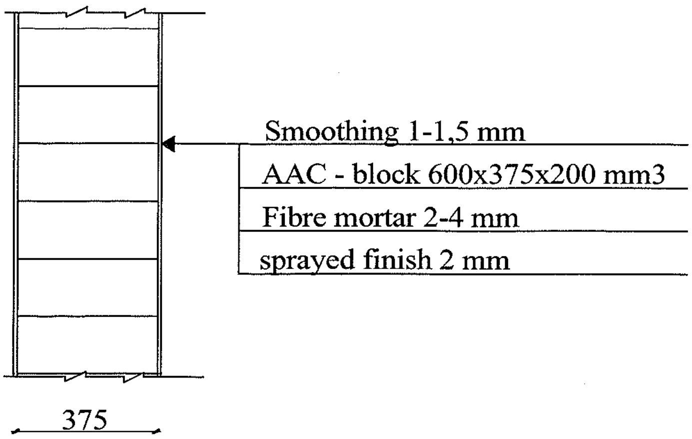
Details of the external walls



Polyurethane insulated wooden frame wall



Insulated log wall



Autoclaved aerated concrete block wall

APPENDIX 6

Ventilation System's technical specification

Dimensions of the systems

Height	480 mm + duct connections
Width	585 mm
Depth	430 mm
Voltage	230 V/50 Hz

Fans (2 units)
Power 2 x 105 (max.)
Current 0.45 A

Preheating (Ex S)	600 W electric resistor Thermostat controlled and re-settable overheating prevention
Fan adjustment	The quantity of air is selected from the control panel with four set-points
Condensed water unit	Copper pipe - 15 mm diameter. In working form it involves a copper water tap

LEGEND

a. Heat exchanger plates
b. Extract air fan, 105 W (max.)
c. Supply air fan, 105 W (max.)
d. After-warming resistor or battery
e. Plug
f. Condensed water pipe (water tap)
g. Pollen filter
h. Extract air filter

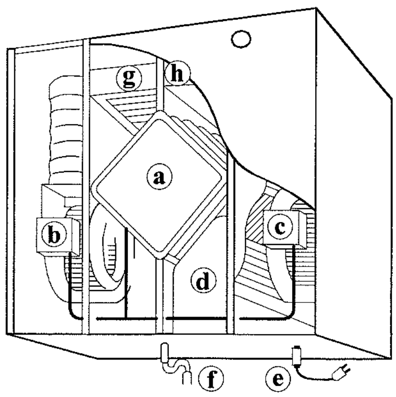


Figure A6.1: Ventilation system (PARMAIR IIWARI EX)

MANUFACTURER:
LVI-PARMAIR Oy, Yrittäjänkaari 23
30420 FORSA, FINALND
Tel. +358 3 422 6999, Fax: +358 3 422 6989

LEGEND

1. Extract air (HRD → outside)
2. Supply air (outside → HRD)
3. Supply air (HRD → room)
4. Extract air (room → HRD)

HRD = Heat Recovery Device
→ = From - to

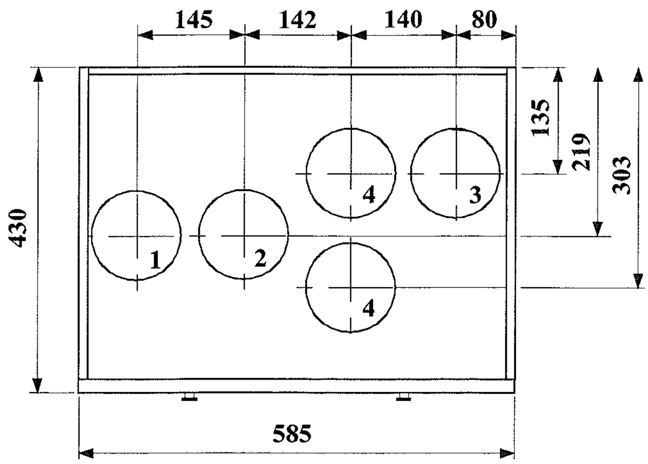


Figure A6.2: Ventilation system's top view

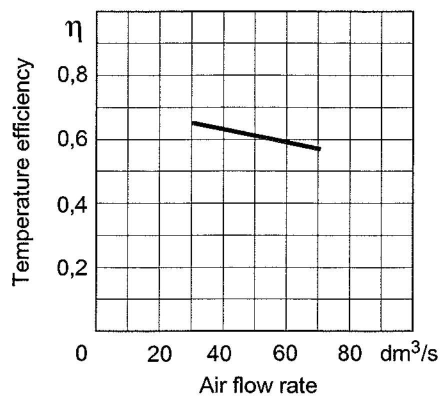


Figure A6.3: Heat transfer efficiency of the Heat Recovery device

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THE IMPACT OF AIR TIGHTNESS OF THE BUILDING ENVELOPE ON THE EFFICIENCY OF VENTILATION SYSTEMS WITH HEAT RECOVERY

This publication presents the research findings regarding the impact of building envelope air tightness on energy perfomance of mechanical ventilation systems with heat recovery. The study covers theoretical as well as practical methods of determining the quanity of infiltration air in buildings. Three test buildings, constructed of different building materials and, having different degree of air tightness were tested. The buildings were ventilated by using balanced mechanical ventilation systems with air-to-air heat recovery. Equations for predicting the quantity of uncontrolled air changes and hence the annual infiltration energy losses in buildings due to various wind speeds were developed and are herein presented. Heating degree-days for the prevailing weather conditions, including ventilation and infiltration air change energy losses were calculated. The quantity of heating energy that can be recovered throught ventilation heat recovery under various degree of envelope air tightness is investigated. The influence of the severity (coldness) of the climate on heat recovery efficiency of ventilation systems is analysed. Using an “Example Building”, the implication of the degree of envelope air tightness to the overall heating energy consumption in a normal residential building is examined taking into consideration different ventilation strategies and different building´s average U-values.

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